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As North Carolina experiences population growth and related development, it will become increasingly important to understand how different land-use/land-cover (LULC) types shape the geography of water quality. This dissertation explores the relationships that exists between water quality and land types across the Cape Fear River Basin, North Carolina. Key water quality parameters including fecal coliform, dissolved oxygen (DO), ammonium nitrogen (NH3-N), phosphorus (P), and nitrate-nitrite nitrogen (NO2-NO3), and LULC types were quantified and spatially illustrated to understand how relationships varied across the river basin from 2001 to 2006. Regression models were developed to statistically link water quality parameters with LULC types across the river basin and within each of the physiographic regions. Results indicate that this diverse landscape contributes varying amounts of pollution to surface waters within the basin. Specific findings include that although there was little change in land types during the study period, there were statistically significant relationships between land types and surface water quality. Although regression models illustrate that each of the dependent variables contributed some level of pollution to surface water systems in the basin, fecal coliform, and DO concentrations, in particular, were impacted by key land types including wetlands, mixed forest, and exurban development. In addition, there were regional differences among the three physiographic regions and water quality parameters. The primary findings suggest that transitional land types (i.e. mixed forest and exurban development) that surround urban cores can play a key role in shaping the geography of water quality across the river basin. As a result, resource agencies and decision makers alike should consider how land-use policies and activities related to transitional landscapes may adversely impact surface water quality across river basins.

LAND-USE/LAND-COVER AND WATER QUALTY IN THE CAPE FEAR RIVER BASIN,

NORTH CAROLINA: SPATIAL-TEMPORAL

RELATIONSHIPS

by

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DEDICATION

I would like to dedicate this dissertation to my son, Michael Jordan Alford. I hope this research will play a vital role in protecting the priceless water resources that collectively make North Carolina a truly unique and amazing place to grow up, explore, and play. My hope is that this dissertation and the future research efforts it may support will encourage decision makers at the local, regional, and statewide levels to consider the dire impacts of not protecting this precious resource for future generations to come.

APPROVAL PAGE

This dissertation written by JENNIFER BRASWELL ALFORD has been approved by the following committee of the Faculty of The Graduate School at The University of North Carolina at Greensboro.

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CHAPTER I

INTRODUCTION

There are over 3.6 million miles of rivers and streams in the United States each exhibiting unique characteristics that are physically, biologically and chemically influenced by the diverse landscapes they traverse (EPA, 2010 a). As water flows across land surfaces, it collects and transports inputs, such as nutrients and sediment, to surrounding surface water bodies including rivers, streams, and lakes. Over time, this process impacts the biological, physical, and chemical characteristics of the receiving water bodies (Tong & Chen, 2002; Mallin et al., 2009; Brabec, 2009; Myer et al., 2005). Over the past several decades, point source and non-point source pollution (NPSP) inputs to rivers systems have increasingly impaired surface water quality in local and regional watersheds (Carpenter et al., 1998; Mallin et al., 2009; Brabec, 2009, Liu et al. 2002). NPSP alone accounts for approximately 70 percent of surface water degradation in the United States (Potter et al., 2004). Deterioration of surface water quality from anthropocentric sources is typically associated with various socio-economic activities within a region, such as the amount and type of developed or cultivated land within a river's drainage basin. Land-use/land-cover (LULC) such as urban, forest, and agriculture have varying impacts related to the amount of NPSP they contribute to river and stream systems. Once in surface water systems, NPSP can be transported downstream reaching additional subbasins often resulting in the contamination of isolated surface waters. Given this geographical context, the scale at which water quality deterioration may take place is both local and regional (Hascic & Wu, 2006).

The relationships that exist between different landscape types and surface water quality have been well documented in multiple disciplines including, but not limited to, geography, hydrology, marine biology, and environmental planning (Mallin et al., 2009; Meybeck & Helmer, 1989; Tong & Chen, 2002; Rothenberger et al., 2009; Tu, 2011; Booth & Jackson 1997; Arnold & Gibbons, 1996). Within geography, the spatial distribution of water has been a central concern of the discipline (Fonstad, 2013). One prominent theme in the geography of water is the spatial analysis of water quality as it relates to both water supply and management as highlighted in the 2013 special issue of the *Annals of the Association of American Geographers* on the "Geographies of Water". A key research issue in this arena includes better understanding of how the cumulative effects of multiple land-use/land-cover (LULC) types and landscape patterns and activities within the same drainage basin can negatively impact water quality at both the local and regional scales (Randhir & Hawes, 2009). NPSP, such as mercury, sediment, phosphate, nitrate, and fecal coliform, have been tied to specific LULC types, including urban, suburban, industrial, and agricultural areas (NC DENR, 2005). For example, Tong and Chen (2002) noted that runoff from agricultural landscapes may be enriched with nutrients and sediments, while urban landscapes may contribute to higher concentrations of heavy metals and sodium. Despite these challenges, only 19 percent of streams and rivers in the United States have been assessed by federal and state agencies indicating that relatively little is known about the spatial extent of impaired stream and river systems (EPA, 2013). Ensuring that natural water resources are clean is critical for safe municipal drinking water, irrigation for crops, industrial uses, supporting biological diversity and aesthetic enjoyment (EPA, 2010 b; Brabec, 2009; Carpenter et al., 1998).

Although some geographical studies have observed that relationships exist between different LULC and water quality (Tu et al., 2007; Tu, 2011; Su et al., 2012), these studies typically considered these relationships at the local watershed scale or by observing a portion of a river basin. Although government agencies have conducted extensive studies related to water quality and land types, this research focus has been less common in the discipline of geography. The Cape Fear River Basin (CFRB) in North Carolina is one example of just such a river basin that includes three distinct physiographic regions, which encompass six subbasins that are defined by their surface hydrological characteristics. These physiographic regions (i.e the Upper CFRB, Middle CFRB, and Lower CFRB) and subbasins may have interactive effects as the river and its tributaries move from the headwaters to the mouth of the basin. The Upper CFRB includes clay soil types and varying topography, while a sand hill terrain dominates the Middle Cape Fear, and blackwater systems and coastal estuaries characterize the Lower Cape Fear River Basin. Analysis of the spatial variation of water quality at three different physiographical regions and their subbasins is critical if we are to better understand how different LULC types in different settings impact the ecology of the entire river basin network.

The overall purpose of this dissertation is to quantitatively evaluate and spatially illustrate how changes in LULC types at multiple geographic scales influence water quality throughout the entire Cape Fear River Basin. The Cape Fear River Basin was selected because it is the most densely populated river basin in North Carolina as well as the largest physical river basin (24,086 km^2) completely enclosed within the state. Collectively, the physiographic regions of the CFRB embody a variety of different LULC types that contribute to point and non-point sources of water pollution (NC DENR, 2005). Land-use/land-cover types may include urban, industrial, forested, and agricultural areas. In addition to being the most densely populated river basin in the state, the basin is the most industrialized and contains the highest concentration of swine (e.g. an estimated 5,000,000 heads of swine), which contribute varying amounts of NPSP to surface waters within the basin (Mallin, 2012). Although previous research focused on the CFRB has demonstrated that some relationships exist between LULC types and water quality (Mallin et al., 2001; Mallin et al., 2009), these studies do not comprehensively address these relationships across the entire river basin. In an effort to understand and illustrate how LULC types and patterns influence water quality, specific land types and characteristics will be observed across the CFRB at multiple geographical scales including across the entire river basin and each of the physiographic regions. Some of the key research questions posed in this dissertation include how and to what extent landscape types influence surface water quality across multiple geographical scales. More detailed research questions will address how different types of developed and agricultural land influence surface water quality throughout the CFRB.

According to the United States Environmental Protection Agency (EPA) only 12,079 miles (32 percent) of North Carolina's rivers and streams have been assessed for water quality impairment indicating that little is known about the full spatial extent to which the state's rivers are impaired (EPA, 2013). As North Carolina experiences population growth and related development, it will become increasingly important to understand how the landscape and its patterns affect local and regional water quality. This research will add to the growing literature that seeks to understand how variations in LULC types and landscape characteristics influence surface water quality. Taking a geographical approach to this topic presents a unique contribution to the literature because it enables one to understand the complex relationships that exist between the socio-economic impacts on the landscape and their relationships to the physical, chemical, and biological characteristics of water quality throughout the entire river basin.

CHAPTER II

LITERATURE REVIEW

In an attempt to link findings in the literature to the research questions under investigation, specific literature that observes relationships between land-use/land-cover (LULC) and water quality in varying locations as well as research conducted in the Cape Fear River Basin will be reviewed. The goal of this literature review is to highlight established relationships between land types and water quality so that these findings can be compared to methods and results employed in this study. In doing so, this review will assist in identifying what gaps exist in the literature so that a more comprehensive approach to assessing spatial-temporal relationships between land types and water quality across the entire river basin can be developed and implemented. The review will include specific land types and their potential impacts on surface water resources as well as the role of how landscapes that transition from one land type to another influence surface water quality. In addition, specific methods that support these evaluations will be included to highlight how different methods can be employed to analyze and illustrate these relationships across various landscapes. Addressing the numerous approaches in the literature will further underscore how this study will add to the growing literature that seeks to understand how different landscape characteristics and types impact surface waters across an expansive heterogeneous landscape, such as a river basin.

Land-Use/Land-Cover and Surface Water Quality

In an effort to identify different landscapes within a region, land-use/land-cover (LULC) is a term used to describe the general land-cover (e.g. developed, water, forest, wetlands, cultivated), while LULC types give an indication of specific activities on the landscape that may take place within a given LULC type (e.g. high intensity development, cultivated crops). Numerous studies have concluded that certain land types contribute different types and quantities of NPSP when compared to other land types in the same study area (Tong & Chen, 2002; Mallin et al., 2000; Mallin et al., 2009; Carle et al., 2005; Rothenberger et al., 2009). When examining the influences of runoff from different land types on surface water quality, Tong and Chen (2002) suggest that agricultural areas typically contribute higher concentrations of nutrients and sediments when compared to other areas. Nutrient concentration (e.g. phosphates and nitrates) may be due to fertilizer applications to crops in an effort to increase crop production and sediment concentrations may be related to soil disturbances including tilling the land to prepare it for crop planting. In contrast, runoff from urban areas may contain rubber fragments, heavy metals, sodium, and sulfates from road debris. Dominant LULC (e.g. greater than 50 percent agricultural, urban or forested land) within a watershed also serves as a method for linking LULC types to specific water quality parameters. Several studies (Lenat & Crawford, 1994; Mallin et al., 2009 and others) have observed specific water quality parameters related to the dominant land type found within a given watershed. In a study of three North Carolina piedmont watersheds dominated by urban, agricultural, and forested landscapes, Lenat and Crawford (1994) note that although the watersheds did not have impaired levels of water quality as defined by state water quality guidelines, certain water parameters were associated with specific land types including urban, agricultural, and forested. For example, total suspended solids (TSS) were greatest in the urban stream and least in the forested stream while concentrations of metals were slightly elevated in the urban watershed when compared to the forested and agricultural stream catchments.

In a study conducted in the Lower Cape Fear River Basin, Mallin et al. (2009) observed the impacts of stormwater on water quality in an urban, a suburban, and a rural stream. The study concluded that the percent watershed development and percent impervious surface coverage within a watershed were positively correlated with specific water quality parameters including biological oxygen demand (BOD), orthophosphates, and surfactant concentrations but negatively correlated with total organic carbon. The urban and rural streams showed the greatest variations in water quality parameters. The urban stream yielded the highest concentrations of BOD, orthophosphates, total suspended solids (TSS), and surfactants, while the rural stream had the highest total organic carbon concentrations of the three assessed streams. The study attributed these differences to varying characteristics that define the urban and rural catchments. In the urban catchment there was a significant increase in development and consequent impervious surfaces, while the rural catchment was characterized by significant agricultural practices (e.g. livestock grazing).

Given the complex nature and varying characteristics of landscapes and their spatial distributions, it will be increasingly important to understand the spatial extent to which land-use/land-cover (LULC) impact surface water quality. Surface water quality at the local and regional scales are important to support both natural and anthropocentric uses including water resources for drinking and irrigation as well as supporting complex ecosystems that are unique to the Cape Fear River Basin. Over the past thirty years, landscape patterns in North Carolina have transitioned from one largely dominated by agricultural and forestland to one that is becoming increasingly urbanized (i.e. industrial, commercial, and residential) (NC DENR, 2005). Several studies in North Carolina have linked urban and agricultural areas with impaired water quality (Mallin et al., 2001; Mallin et al., 2009; Rothenberger et al., 2009; Lenat & Crawford 1994), however, they have not considered these impacts across a large hydrological extent that traverse a variety of regional landscapes, such as the Cape Fear River Basin. Given these findings, it will be important to focus on how these LULC characteristics impact surface water quality as well as how these relationships compare and contrast with natural landscapes.

Urban

On a global scale, human populations are increasing in urban areas with approximately half of the world's population living in urbanized areas. Growth in population drives increases in developed land, which promotes changes in surface water quality. Urban areas are typically developed along river corridors that provide water resources for human consumption such as drinking water and industrial uses (O'Driscoll et al., 2010). In the United States, dispersed urban land patterns began to emerge after the Second World War as a result of federal housing and transportation policies, including The Housing Act of 1954 and the Federal-Aid Highway Act of 1956. Collectively these policies enabled individuals to purchase single-family homes outside the urban core, spurring major development of residential homes and related service industries as well as transportation corridors including federal interstate and beltways systems. Urban form in the USA has transitioned from one characterized by high-density development to one with both high-density and low-density development resulting in dispersed development patterns (Lang & Knox, 2009; O'Driscoll et al., 2010). Urban watersheds are typically characterized by a higher level of impervious surfaces and drainage systems designed to prevent flooding by efficiently removing stormwater from buildings and streets. This infrastructure design has resulted in increases in stormwater runoff volumes, higher peak flows in streams, and a reduced ability of soils to remove pollutants through soil infiltration and plant uptake processes (Corbett et al., 1997; Meyer et al., 2005; Walsh et al., 2005). Land-use policies, such as zoning, also play a role in determining the location and characteristics of land types. Arnold and Gibbons (1996) suggest that within an urban environment, commercial, and industrial land types typically consist of 95 percent impervious coverage while residential areas show a wide range of impervious surface cover that vary with lot size and may be from 20 percent impervious cover in one-acre zoning to as high as 65 percent impervious surface in a 1/8 acres zoning category. As North Carolina continues to increase in population, resulting in an increase in developed areas, it is important to consider how different urban forms (e.g. high and low-density development) impact surface waters that support both anthropocentric and ecological functions.

Urban Landscape Features and Water Quality

Like other landscapes, urban land-use/land-cover (LULC) can have numerous effects on surface water quality including chemical, biological and physical changes in addition to altering the natural regime of surface and subsurface hydrological systems. The influence of urban areas on water quality may be highly variable and may depend on multiple landscape features including the age and type of urban development, the presence or absence of wastewater treatment plants (WWTP), the stormwater infrastructure, the presence of vegetative stream buffers, natural hydrologic regiments, and the historical and present land activities. Hydrological and geomorphic changes to stream functions as a result of urban development can compound the effects of a single pollutants' influences on water quality resulting in drastic changes in stream ecosystem functions. The potential results of these changes may include permanent alteration or fluctuations in surface water temperature, increased concentrations of nutrients and heavy metals, and a reduction of dissolved oxygen needed to sustain aquatic species health and diversity (Arnold & Gibbson, 1996; Carle et al., 2005; Walsh et al., 2005; Viau et al., 2011; Smucygz et al., 2010; Booth & Jackson, 1997; Miserendino et al., 2011).

In an effort to identify specific urban landscape features that convey NPSP to surface waters, several studies (Carle et al., 2005; Mallin et al., 2000; Hatt et al., 2004; Booth, 1991; O'Driscoll et al., 2010) have considered landscape indicators of urban development patterns, the type of urban density (i.e. low density, high density), and the role of impervious surfaces (connectivity) in conveying stormwater to surface waters. Carle et al. (2005) considered the type and density of urbanization and access to municipal services as indicators of urban growth patterns when observing six urban watersheds in Durham, North Carolina. In addition to response variables including total nitrogen (TN), total suspended solids (TSS), and fecal coliform, Carle et al. (2005) assessed indicators of urbanization including two variables related to density (percent impervious surface area and household density), four variables related to type of urbanization (percent connected impervious surface area, mean impervious surface patch size, median impervious surface patch size, and median house age), four variable related to access to city services (density of sewer system connections, septic tank density, stormwater outfall density, and percent of the watershed inside the city limits), and five variables related to natural watershed features (hydric soil density, mean saturation hydraulic conductivity, mean soil erosivity, and wetland density). Principal Component Analysis (PCA) was applied to explore the variation of the explanatory variables across space in the urban landscape. Results indicate that 85 percent of the variance in the data are found in the indicators, urbanization density, urbanization type, access to city services, and soil properties. In relation to specific water quality indicators, development density was correlated to increases in TN, TP, TSS and fecal coliform. It was also noted that while urbanization density is an important factor in predicting water quality, the type of urbanization and access to city services can improve existing watershed models because it can assist in illustrating the extent of urban development (Carle et al. 2005).

Wastewater treatment plants (WWTPs) are considered a point source of water pollution and have been correlated with increases in pathogens and nitrate-N loadings in local and regional rivers and stream systems (Smith et al., 2001; Ahearn et al., 2005). When characterizing the impacts of WWTPs on surface water quality in the Sierra Nevada region of California, Ahearn et al. (2005) observed the influence of human development and population density on total suspended solids (TSS) and nitrate-N loadings in stream systems. In this study, WWTPs were correlated with increases in nitrate-N levels, however increases in nitrate-N levels did not correlate with increases in urban areas with in a subbasin. The authors argue that this is a significant finding because it implies that urban areas alone may not serve, as an indicator of increases in nitrate-N loading in a localized stream system, however, there was a significant connection between urban areas and nitrate-N loading when WWTPs were located within the urban landscape.

Pathogens, including fecal coliform, have been linked to urban and suburban human development and related infrastructure. Mallin et al. (2000) observed the effects of human development on water quality in a series of tidal creek watersheds located in the largest river basin in North Carolina, the Cape Fear River Basin. Located in New Hanover County, the watersheds are characterized by rapid development along coastal regions and salt and freshwater aquatic habitats. By 1990, watersheds in this region had been classified as either fully or partially closed to shellfishing due to increased bacterial counts. This study investigated five watersheds, Howe Creek, Pages Creek, Hewletts Creek, Futch Creek, and Bradley Creek, all with similar geographical, climatic, and soil characteristics, but varying amounts and types of development and population density. In relation to land types and development, the study found that fecal coliform pollution was positively correlated to watershed population, percent developed watershed, and strongly correlated with percent impervious surface coverage. For example, Howe Creek watershed yielded higher average fecal coliform than Pages Creek watershed, despite the fact that Howe creek watershed was less developed. Mallin et al. (2000) conducted further analysis that revealed that 27.3 percent of the developed land around Howe was impervious, while 12.5 percent of the developed land in Pages consisted of impervious coverage. In addition, the design of the stormwater catchment system, such as curb and gutter street systems, significantly altered water quality. The study suggests that future research should focus on a more in-depth assessment of the bacteriological quality of water draining from specific types of urban design, the quality of water draining from specific suburban housing development types, and how effective systems such as wetlands and vegetative buffers are in reducing NPSP loads.

Impervious Surface and Water Quality: Total Verses Effective Impervious Area

Impervious surfaces can serve as surrogate indicators of developed land and can contribute to hydrologic changes at both the surface and groundwater scales. In addition, impervious surfaces may cause ecological changes that may hinder the removal of pollutants through infiltration processes (Arnold & Gibbons, 1996). A significant amount of attention has focused on analyzing specific physical features that convey stormwater runoff from urban and suburban areas to nearby river and stream systems (e.g. stormwater drainage systems). Impervious surfaces, including streets and buildings, have been identified as effective stormwater runoff conveyance systems that have been linked to adverse impacts on surface waters. It is important to note that impervious surfaces serve as an effective system for transporting pollutants to stream and river systems. Two measurements of impervious surface have emerged in the literature: (1) Total Impervious Area (TIA), which considers all of the impervious area within a watershed regardless if it is directly connected to the stream system or not and (2) Effective Impervious Area (EIA), which only considers the impervious structures that are physically connected to the stream system such as stormwater drainage systems, gutters from buildings and ditch systems (Arnold & Gibbons, 1996; Booth, 1991; Brabec, 2009). As a result, the literature has varying conclusions regarding the relationships that exist between impervious surfaces and surface water quality. Booth (1991) argues that using percent TIA can lead to misconceptions about the influence of impervious areas on stream health. Instead, he argues that percent EIA should be considered because it can physically link specific land-use activities with stream water quality. In an extensive literature review on the effects of urbanization landscapes on watershed hydrology and in-stream process in the Southern United States, O'Driscoll (2010) concluded that EIA has been shown as a robust metric for illustrating the spatial connectivity between impervious areas, stream water quality and ecological health.

Hatt et al. (2004) considered the influence of urban density and drainage infrastructure on the concentrations and loads of pollutants to streams to characterize stream water quality in the Melbourne, Australia. Water quality variables included temperature, pH, electrical conductivity (EC), total suspended solids (TSS), total nitrogen (TN), total phosphorus (TP), nitrate/nitrate, dissolved organic carbon (DOC), filterable reactive phosphorus (FRP), and ammonium nitrogen (NH3-N). Stream baseflow measurements and rainfall-runoff models were used to estimate the pollutant loads of the water quality variables under investigation. Stormwater drainage connection to streams and imperviousness at the subbasin scale were used as indicators of urban density. Results indicate that at low levels of imperviousness, stream water quality degradation was highly correlated with EIA verses TIA when considering the amount of landscapes covered by impervious surfaces alone. These results support similar findings (Booth et al., 2002; Finkenbine et al., 2000; Brabec, 2009; O'Driscoll, 2010) that argue that the percent EIA is a better indicator of impervious surface impacts to stream systems in comparison to using percent TIA. Brabec (2009) notes that in addition to considering TIA and EIA, the location of impervious surfaces within a watershed also plays a critical role on surface water quality. Although there is an abundance of studies that consider relationships between LULC and water quality, few quantitative relationships have been established between percent impervious surface and the geographic extent of impervious surfaces in relation to surface waters and stream water quality.

Urbanization and In-Stream Processes

Urban areas consist of a variety of high and low-density development that typically encompasses commercial, residential, and industrial development that has varying impacts on surface water quality and stream ecology. Impacts to stream systems may include physical, hydrological, chemical, and ecological changes due to hydrological alterations and channel disturbances along stream banks (O'Driscoll et al., 2010; Grimm et al., 2008). In characterizing streams ecological responses to urban development, several studies (Walsh et al. 2005; Meyer et al., 2005; Finkenbine et al., 2000; and others) observed consistent patterns related to urban landscapes and the ecological degradation of streams, often termed the *urban stream syndrome* (Walsh et al., 2005). Consistent symptoms of the urban stream syndrome include a flashier hydrograph profile indicating short periods of higher flow events, elevated concentrations of nutrient and contaminant inputs, altered channel morphology and bank stability, and reduced biotic richness. Hydrological changes include more frequent, larger flow events with faster ascending and descending hydrograph profiles. The rapid increase of stormwater to stream systems is associated with stormwater systems that convey stormwater from impervious surfaces such as roads and buildings. This process may hinder stormwater's ability to infiltrate into soils, a process that not only removes pollutants but also recharges groundwater systems that contribute to a streams base flow. The increased velocity and quantity of stormwater from impervious surfaces can cause bank channel incision and bank erosion, which introduces an increase of fine sediments to stream systems. This process can smother aquatic species breeding grounds and hinder the growth of aquatic plant by blocking sunlight needed to sustain photosynthetic processes (Meyer et al., 2005; Paul & Meyer, 2001; Walsh et al., 2005). Collectively, these processes alter the streams physical, biological, and chemical attributes with both short-term and long-term effects.

When observing the impacts to streams in urban settings, it is important to consider the physical composition of stream banks. Vegetated strips or buffers along stream banks have been identified as an important landscape feature in promoting stream bank stabilization resulting in improved water quality and ecological health. In its natural state, this zone serves as a mechanism for protecting stream banks from bank erosion during overland flow events as well as adding large woody debris (LWD) to the stream systems, which supports the development of diverse aquatic habitats and nutrients for benthic invertebrates in addition to providing shelter for fish during high flow events (Finkenbine et al., 2000). As runoff volumes increase in stream systems, erosion of stream banks increases the undercutting of stream banks, which may cause banks to collapse. This process can increase the amount of sediments in the stream system leading to increases in total suspended solids and related turbidity as well as leading to the removal of vegetation along the stream banks both locally and downstream. Paving over natural landscapes also reduce the amount of precipitation contributing to groundwater systems, further starving vegetative stream buffers of subsurface water resources, which play a vital role in maintaining vegetated habitats during periods of prolonged drought (Arnold & Gibbons, 1996).

In an effort to identify the locations of impaired streams and to develop stream rehabilitation priorities, Finkenbine et al. (2000) observed several streams located near the highly urbanized area surrounding Vancouver, British Columbia. The watersheds under investigation have been urbanized for over 20 years with TIA ranging from 5 to 77 percent. Methods of stream assessment included analysis of base flow, stream width, depth and velocity, composition of bed materials, the presence of large woody debris (LWD), and measurements of bank erosion. Results indicated that the aquatic species showed signs of recovery from development activities in the watersheds and impervious surface played a role in changing the streams from their natural state. During the construction phase, streams went through physical and biological changes related to increases in peak flows, which caused channel bank erosion. During this process, LWD (e.g. tree limbs) needed to provide aquatic species with habitat and shelter were removed and higher amounts of sediments were introduced into the stream system. After the construction phase, the streams began to stabilize as indicated by less severe changes in stream channel morphology, however, Finkenbine et al. (2000) indicated, slightly higher peak velocities, decreased base flow, lack of LWD and vegetated riparian integrity are still common problems hindering the streams abilities to return to their natural state even after development has ceased.

Urbanization Thresholds and Stream Ecosystem Health

Stream ecosystem functions not only vary in relation to different urban landscape features, they also show considerable variation in response to different levels of urbanization. To characterize the level of development within a watershed and its impacts on in-stream ecological health, numerous studies (Arnold & Gibbons, 1996; Mallin et al., 2001; Schueler, 1994; Schiff & Benoit, 2007; Wang, 2001) have identified thresholds at which the percentage of a particular LULC within a catchment impacts aquatic habitats. Several studies have used percent impervious surface as an indicator of stream and aquatic species health and concluded that the health of aquatic species begins to decline once the watershed reaches 10 to 15 percent impervious surface coverage. When considering the impacts of residential and suburban development in coastal watershed, Mallin et al. (2001) noted stream impairment at 10 percent watershed impervious surface. Schiff and Benoit (2007) concluded that degradation starts at greater than 5 percent and impairment begins to plateau when the watershed exceeds 10 percent impervious surface. This indicates that no significant changes in stream condition occurred once the watershed reached greater than 10 percent impervious surface. In addition, Holland et al. 2004 found that fecal coliform contamination began at 10 percent impervious coverage, but chemical contamination occurred at 25 to 30 percent. Given these varying results, it is important to consider not only the extent of development but also how these patterns impact the overall health of stream ecosystems that support and sustain aquatic species.

In an attempt to characterize stream ecosystem functions related to different levels of urban development, Meyer et al. (2005) considered the functional characteristics of six tributaries of the Chattahoochee River near Atlanta, Georgia. Variables considered in this study related to the catchment landscape and ecosystem characteristics. Specifically, these variables focused on specific measures of nutrient removal and the amount of fine benthic organic matter (FBOM), which provides an energy source for benthic organisms and microbes. Results indicate that nutrient uptake velocities in ecosystems, such as precipitation and stormwater runoff infiltration into soil profiles, decreased as indicators of urbanization increased, specifically, the percent of catchment covered by high intensity urban development characterized by contiguous impervious surfaces. In addition, the amount of fine benthic organic matter (FBOM) also decreased with increasing urbanization and uptake velocities of nutrients were directly correlated to FBOM. When considering different instream responses to measurements of EIA and TIA, Meyer et al. (2005) noted that channel instability is consistent when the EIA is greater than 10 percent and uniform low summer base flows are observed when TIA is greater than 40 percent. Biological impacts included consistently higher algal blooms when EIA exceeds 5 percent and decreases in fish species quantity and diversity above 4 percent TIA and between 2 to 4 percent EIA.

Schiff and Benoit (2007) explored the impacts of urbanization on streams in the West River watershed located in, New Haven, Connecticut in an attempt to identify the spatial scale of watershed imperviousness and its relationship to water chemistry, macroinvertebrates, and physical habitat. A multiparameter water quality index was used to characterize regional urban NPSP levels. In an effort to address the spatial context of development and impairment, the study compared instream variables to impervious cover at three spatial scales: watersheds, local contributing areas, and streams with an 100-meter vegetative riparian buffers. Water quality parameters included temperature, conductivity, pH, dissolved oxygen (DO), and turbidity. Macroinvertebrates were also sampled once in the spring 1999 at 13 sites, three on the mainstem of the watershed and 10 on tributaries. Results indicate that total impervious area (TIA) in the watershed draining to each macroinvertebrates collection site varied between 0 and 61 percent. Seven of the watersheds had less than 5 percent TIA, five had moderate coverage between 5 percent and 20 percent, and one watershed was highly impervious with a TIA of 60 percent or more. Water quality declined sharply as impervious area increased from 0 to 10 percent and remained in a degraded state beyond the 10 percent imperviousness level.

Urbanization develops in a variety of forms and spatial extents that are largely driven by socioeconomic preferences. The North Carolina DENR (2005) notes that the CFRB alone has experienced a significant transition from areas dominated by agricultural and forest areas to urban development characterized by both low and high-density development types. Various disciplines including marine biology, environmental management, ecology, and geography have noted the adverse impacts of different urban areas on surface water quality and stream and river systems. Noting the clear link between population growth and increases in urbanization, it is important to understand the extent of these impacts at the local and regional watershed scales in an effort to mitigate adverse impacts to surface water quality.

Agriculture

Agricultural landscapes may include crop production, livestock operations, and silviculture practices, each contributing different types and amounts of water pollution to surface waters (Ensign & Mallin, 2001; Mallin et. al., 2001; Schwabe, 2001; Smith et al., 2013; Kasprak et al., 2013; Imaizumi & Sidle, 2012; Zhu et al., 2012). Charbonneau and Kondolf (1993) argue that agricultural landscapes are a more significant contributor to NPSP than any other land types due to their vast spatial extent. Zhu et al. (2012) notes that seasonal variability in water quality may be related to fertilizer and manure applications on farmland or fields. For example, they observed increases in nutrient concentrations in surface waters in a watershed dominated by agricultural areas prior to the growing season and after crops were harvested. When considering livestock production, Mallin and Cahoon (2003) note that the industry has become more industrialized and swine, poultry, and cattle livestock are largely raised and fed in enclosed concentrated animal feeding operations (CAFOs). As a result of the transition of livestock production from open pastures to large building facilities, the concentration of nutrients entering surface water systems where these operations are located has increased. In the Cape Fear River Basin alone, there are an estimated 5,000,000 heads of swine. Several studies (Rothenberger et al., 2009; Mallin & Cahoon, 2003; Burkholder et al., 2007) concluded that an increase in the number and density of CAFOs has significantly increased nutrient inputs to surface waters in North Carolina.

Other types of agricultural activities may include silviculture practices and intense dairy production. Silviculture practices include clear-cutting of forest for lumber and paper production. This practice may strip the land of vegetation, which typically leads to an increase in overland runoff causing more sediment to enter river and stream systems. In addition, this practice may include the application of fertilizers in an effort to increase vegetative growth potential on pastures, further adding NPSP inputs to nearby and downstream surface water systems (Imaizumi & Sidle, 2012; Zhu et al., 2012). Dairy production may impact surface water quality by increasing the amount and frequency of nutrients (i.e. nitrogen and phosphorus) entering surface waters. This is largely related to fertilizer applications needed to grow pasture vegetation as well as livestock feed that is spread onto the surface of pastures and manure runoff (Smith et al., 2013). Agricultural activities vary not only in the type of activities, but also in relation to their spatial context at the local, regional, national, and global scales. Understanding how these activities impact water quality will become increasingly important as the world's population continues to expand, which will fuel an amplified dependency on agricultural practices necessary to feed the growing human population.

Silviculture Practices

Forest harvesting activities (e.g. clear-cutting and artificial forest regeneration) may cause adverse hydrogeomorphic processes within a watershed including an increase in landslides and debris flows. These events result in modified sediment transport rates and ecological changes in river and stream channels. Logging activities support the development of lumber for building materials and furniture as well as pulp to produce paper products. The impacts of logging activities vary by location due to different topographical terrain, climatic conditions, soil types, and slope gradients. The occurrence and amount of sediment transport strongly depends on the timing, landscape slope, and magnitude of rainfall events in addition to the amount and type of vegetation cover and root cohesion within the harvested area (Imaizumi & Sidle, 2012; Kasprak et al., 2013). Imaizumi and Sidle (2012) note that sediment yields may be stored in catchments as hillslope deposits, talus slope, and channel deposits suggesting that sediment transport in rivers and streams may not correspond in time with landslide events that are induced by forest harvesting.

When considering the effects of forest harvesting on four catchments in central Japan, Imaizumi and Sidle (2012) observed the impact of this practice on hydrogeomorphic processes in areas characterized by steep terrains. Approximately 95 percent of the total catchment was converted from a natural forest landscape to an industrial managed forest with the remainder of the catchment utilized for forest logging roads, log landings and secondary broadleaf forests.

It was study concluded that forest harvesting activities increase the frequency of both landslides and debris flows during periods of heavy rainfall events in the study area. This resulted in changes in both the volume of sediment storage and contributions of sediments to bedloads and suspended sediments in stream channels. As logged forests are artificially re-established, the impacts of forest harvesting decrease due to the establishment of net root strength as evident by a decrease in landslide and debris flows events. Imaizumi and Sidle (2012) suggested that the effects of forest harvesting on hydrogeomorphic processes cannot be assessed by simply observing changes in the elapsed time after forest harvesting. Instead, rainfall magnitude and the history of mass movements of sediment through mass wasting processes need to be considered in an effort to understand the linkages between movement events and the amount of sediment loads reaching stream and river systems within a given watershed.

When considering changes in stream water quality, Ensign and Mallin (2001) observed changes in stream water quality following a 130-acre clear-cut timber harvest Long a streamside in the Goshen Swamp, North Carolina. Dominate land coverage included forest (52.5 percent), agriculture (46 percent), and urban/residential (1 percent). Data was collected monthly for 15 water quality parameters, including physical (temperature, pH, dissolved oxygen, total suspended solids), biological (chlorophyll *a*, fecal coliform bacteria) and nutrients (NH3-N, NO3-N, phosphorus (TP), and Total Kjeldahl nitrogen (TKN)). During the harvest, Best Management Practices (BMPs) required by the North Carolina Division of Forest Resources were implemented and natural vegetation was re-established, without the use of fertilizers or seeding, including a 10-meter streamside, vegetated buffer zone.

Data collected from the Goshen Swamp watershed was compared with a non-clearcut watershed, Six Run Creek, where land activities mimicked the Goshen Swamp, including silviculture practices and 131 concentrations of swine operations contributing to non-point sources of water pollution. The same 15 water quality parameters were monitored in Six Run Creek as the Goshen Creek watershed. Results indicated that clear-cutting reduced dissolved oxygen and increased total nitrogen, phosphorus, suspended solids and fecal coliform bacteria in the Goshen Swamp watershed for the first 15 months after the timber harvest. Recurrent spikes in chlorophyll *a* counts occurred after this period, resulting in longer-term algal blooms. This suggests that an increase in nutrient levels found after clear-cutting can cause long-term water quality degradation downstream. In addition, the establishment of a 10-meter vegetated buffer zone was inadequate in significantly improving water quality at the study site (Ensign & Mallin, 2001).

Confined or Concentrated Animal Feeding Operations (CAFOs)

Confined or concentrated animal feeding operations (CAFOs) may include swine, cattle and poultry production. This industry has developed over the past several decades as pasture livestock production has moved from the field to large building facilities. In these facilities the livestock are confined to small areas where they are fed until they are ready for butchery, sale or trade on the market. Waste products produced by the livestock are deposited on the floor of the facilities and disposed of by washing the waste down trench and pipe systems. The waste is then collected in waste lagoons located outside the facilities where the waste is later disposed of on adjoining fields or through subsurface injection. When applied to the fields, the manure can be sprayed in liquid form or dried and applied as a fertilizer product where plants, such as Bermuda grass and cotton corn, are planted in an effort to absorb the nutrients inherent in the manure products. Adverse effects of these practices include increases of nutrients entering groundwater supplies and surface waters both adjacent to and downstream of CAFO sites. This process can lead to the eutrophication of water bodies harming both the quality of water and aquatic habitats (Mallin & Cahoon, 2003; Burkholder et al., 2007).

Ninety percent of North Carolinas' swine production, a large majority of its turkey production and approximately 30 percent of the state's chicken population reside in the Coastal Plain. To understand the contribution of animal waste on pollutant loads in the Coastal Plain, Mallin and Cahoon (2003) calculated the number of livestock by animal category and estimated the amount of nutrients and bacteria excreted by each type of livestock on an annual basis.

Water quality data was collected from the University of North Carolina at Wilmington's Lower Cape Fear River Program which has monitoring stations located in close proximity of numerous CAFOs in the study area. The study revealed that swine and turkey production contribute the greatest amount of nutrients inputs to the annual waste stream. When considering swine alone, it generated 101,000 metric tons of N, while turkeys generated 12,600 metric tons. In relation to P concentrations, swine generate 22,700 metric tons of P and turkey generated 3,500 metric tons. Mallin and Cahoon (2003) note that this study did not take into consideration nutrients produced by the decomposition of dead animals in the study site, which may have an impact on nutrient loading. For example, heavy and prolonged precipitation related to Hurricane Floyd in October of 1999 resulted in mass flooding of the Coastal Plain, which led to the drowning of numerous livestock. Another NPSP input considered in this study was ammonium, which comprises the largest portion of total N in swine and poultry liquid waste. Ammonium can be transported to surface waters through overland runoff, lateral groundwater flow and atmospheric processes. Data from the Lower Cape Fear River Program indicates that there was a statistically significant increase in ammonia levels in the Northeast Cape Fear River station from 1996 to 2001.

A vast majority of CAFO operations in the Coastal Plain are located in the Neuse, White Oak, and Cape Fear River Basins, which ranked highest in the nation in waters that are vulnerable to NPSP. In the Cape Fear River Basin, which produces 50 percent of North Carolina's swine production, a vast majority of the CAFOs are located in watersheds that are drained by blackwater systems. Blackwater streams are naturally nutrient poor and increases in nutrient loadings can lead to spring and summer algal blooms. In seeking solutions to the impacts of CAFOs on water quality and related aquatic habitat, Mallin and Cahoon (2003) suggest that historically these operations have been considered a non-point source of pollution and thus have been exempt from regulation under the federal National Pollution Discharge Elimination System (NPDES) enacted by the National Environmental Policy Act (NEPA). Regulatory efforts by the state of North Carolina have failed to target the consequences of the spatial concentration of CAFOs, making federal regulation of CAFOs all the more imperative if surface waters are to be protected (Mallin & Cahoon, 2003).

Dairy Farming

Pastoral dairy farming activities have increased in the past two decades as a result of the growing demand in dairy products. As a consequence, concerns have been amplified in relation to how dairy production activities adversely impact environmental quality. Smith et al. (2013) analyzed changes in water quality in three stream catchments located in southwest Victoria, Australia. The purpose of this study was to investigate if water quality had changed in the past 21 years as the intensity of milk production increased in the area. It was argued that water quality changes, especially increases in the import of nitrogen (N) and phosphorus (P), are driven by an increase in the intensity of dairy production at the catchment scale. Intensification, in terms of livestock production per unit area, are driven largely by higher stocking rates coupled with an increase in the use of nutrients in the form of fertilizers and feed from off-farm sources. The increase in nutrients within the catchment altered the land-based nutrient cycle, leading to a substantial surplus of N and to a lesser extent P. Both N and P concentrations increased over the study period and there was a more rapid increase during the 1990s when compared to the 2000s.

It was noted that there were no clear relationships between annual average TN and TP concentrations and total annual rainfall or runoff. When considering changes in farming systems found in the catchment, the intensity of dairy farming was due to a modest increase in farm stocking rates, but mostly the increase was attributed to milk production per cow (i.e. 50 percent increase). Smith et al. (2013) conclude that there was a clear relationship between the increase in dairy farming and concentrations of N and P in the study area. Their study highlights the importance of assessing long term-year datasets at different locations within a catchment when attempting to make comparisons between land-use and water quality.

Agricultural Land-Use Policies and Best Management Practices

Schwabe (2001) analyzed various policies mandated by the North Carolina Department of Environment and Natural Resources (DENR) for reducing pollution inputs from agricultural activities in the Neuse River Basin, which the state recognizes as nutrient sensitive waters. He noted that the basin experienced a doubling of its population and a 50 percent increase in agricultural activities since the 1960's, resulting in a 30 percent increase in annual loading of nitrogen and phosphorus to surface waters. In response to the decline in water quality, DENR developed a rule that required a standard best management practice (BMP), vegetated filter strips (VFS), to be installed on all agricultural land adjacent to intermittent and perennial streams in the Neuse River Basin. After a public comment period about the DENR ruling, the DENR policy became more flexible embracing a variety of nutrient reduction strategies.

Schwabe (2001) developed a model to assess BMP costs related to the DENR policy mandates and their relation to nutrient reduction from agricultural activities in the Neuse River Basin. The model consists of five components: (1) production activities, (2) precontrol nutrient transport, (3) control technologies, such as best management practices, (4) post control nutrient transport and (5) stream transport. In addition, three environmental indices were developed including a slope index, an erodibility index, and transmissivity index. A baseline was developed to compare the cost of installing various BMPs related to nutrient reductions under the DENR policy mandates. Results indicated that the mandatory installation of a standard BMP cost less to install and maintain, but they did not reduce nitrogen loading as well as other BMPs across a wider landscape. Findings include the need for land-use policies aimed at improving water quality that considers the type of policy standard implemented, the amount and type of BMP applications within a watershed, and the stringency of the reduction requirement.

Agricultural land may differ by practice type and spatial extent resulting in varying concentrations and types of pollutants entering stream systems at the local and regional scales. When considering crop production, Zhu et al. (2012) argued that this variation is seasonally related to when crops are planted and harvested. Smith et al. (2013) noted that on pastures where livestock graze, variation in NPSP may be related to the amount and timing of fertilizer applications needed to sustain pasture vegetation for livestock feed. As the livestock industry has transitioned from one characterized by pastures to one characterized by confined industrial facilities where livestock are kept indoors throughout their lives, Mallin and Cahoon (2003) suggest that this increases concentrations of nutrients to waters on a local and regional scale. This is in part due to the application of livestock waste onto fields adjoining river and stream systems in addition to the spatial concentration of CAFOs located within a watershed. As suggested by several studies (Mallin & Cahoon, 2003; Qui & Prato, 1999; Schwabe, 2001), best management practices (BMPs) that address specific agricultural activities and their impacts on surface water quality will need to be implemented if surface waters are to be protected in watersheds where agricultural activities take place.

Natural

Non-point sources of water pollution (NPSP) may occur on natural landscapes, such as disturbed forestlands, and can be transported to wetland ecosystems and through vegetated buffer zones along river and stream systems. Causes of NPSP on forestlands may include increases in sedimentation loads to receiving water bodies as a result of hillslope erosion and overland flow processes. In addition, the amount and type of natural vegetation present in forest have varying impacts related to precipitations ability to reach the ground, which may impact overland runoff rates (Megahan & King, 1985). Binkley et al. (1999) noted that stream water quality in forested areas is typically very good, often exceeding the quality of water in other land types. For example, streams draining agricultural land-types average about nine times greater concentrations of nutrients when compared to streams in forested areas. It should be noted that in areas where forest restoration is taking place, forest fertilization is a common practice for restoring vegetation. During this processes, fertilization applications may increase nutrient concentrations in surface water systems, which may lead to the degradation of nearby water resources.

Wetlands and vegetated riparian areas also serve as natural landscapes that may have an impact on the quality and quantity of surface water resources. Natural wetlands and riparian zones reduce nutrient loadings of through-flowing water by removing nitrate and phosphorus from surface and subsurface runoff. According to Verhoeven et al. (2006), several studies have demonstrated that wetlands have a long-term capacity to improve water quality. This occurs because wetlands have the ability to store runoff for prolonged periods of time, which allows for contaminated water to naturally infiltrate into subsurface systems that essentially remove contaminants from the water. Although wetlands and riparian areas can serve as a mechanism for removing NPSP from surface runoff, overloading these systems may result in ineffective removal of NPSP. In addition, overcapacity of nutrients in these systems may result in the emissions of greenhouses gases and a loss of biodiversity, further impacting the quality of the environment and water quality. To effectively remove NPSP, these systems must be similar in size to the amount of NPSP entering these systems. It has been noted that to remove 40 percent of the nutrient loadings in stormwater runoff, a wetland or riparian area would need to cover at least 5 percent of the catchment area under investigation, although this figure may vary from one location to another (Verhoeven et al., 2006).

Forested Landscapes

Megahan and King (1985) identify critical areas in forestlands that may contribute to NPSP in an effort to guide management and planning techniques to reduce related pollution in watersheds. Critical areas are defined as areas where natural hazards contribute to the production of pollutants at the source or areas that are effective for trapping pollutants en route to water resources. This includes areas of mass erosion, topographical hazards, surface erosion, overland flow areas, and riparian zones. Megahan and King (1985) that erosion processes tend to be greater on forested areas than on most types of agricultural land due to steeper slopes and more shallow soils. Factors such as the type of soil, amount and duration of precipitation, soil infiltration rates and the topography of the forested landscape increase the likelihood erosion will occur within a watershed.

Megahan and King (1985) noted that one of the major contributors of NPSP from forested areas is overland flow, and important filters for improving water quality are riparian zones. Overland flow occurs when rainfall exceeds soil infiltration rates, resulting in the transportation of sediment, one of the primary non-point pollutants in the United States. Megahan and King (1985) assert that this is often rare in undisturbed forested areas; however, areas where excessive rainfall occurs can saturate soils, reducing their infiltration rates and increasing the flow of water over the surface. This process increases the amount and rate in which sediment moves across the forest and into adjacent waterways. Riparian zones include land bordering water bodies such as streams and lakes, which typically include vegetation such as trees and shrubs. Megahan and King (1985) suggested that this zone is recognized as an important and valuable land type because it plays a role in determining the quality of habitat for aquatic species, provided a vegetative buffer zone to assist with protecting water quality that as esthetic value, and provides habitat for terrestrial species. It is observed that specialized management practices in and adjacent to riparian zones are effective tools for reducing non-point sources of water pollution (Megahan & King, 1985).

Wetlands

Wetlands are often considered transitional landscape ecosystems that represent a continuum between terrestrial and aquatic ecosystems. Brinson (1993) noted that wetland functions can be separated into two broad categories: (1) landscape based continua and (2) resource based continua. Landscape based continua include the transition from upstream to downstream riverine wetlands and between terrestrial and aquatic ecosystems within a given wetland system. Resource based continua include the sources of water entering and supporting wetland functions such as precipitation and overland flow as well as the variation of inflows and outflows which may include the import and export of nutrients and sediments. Wetland characteristics can be highly variable and their function may depend on their response to natural and human-induced disturbances and stressors. The sources of water reaching wetlands can lead to functional variations in wetlands. Precipitation-dominated wetlands tend to have low primary productivity and decomposition rates due to their reliance on climatic conditions and patterns. Groundwater dominated wetlands depend on aquifer discharge to maintain soil saturation resulting in higher levels of primary productivity because of the continuous flow of water. Wetlands characterized by overland flow (i.e. tidal and riverine wetlands) have a unique hydrological regiment that is dependent not only on the frequency of precipitation but also how stormwater reaches wetlands. This may result in larger amounts of sediments and nutrients entering these systems when compared to groundwater fed wetlands.

Flood-water storage is another primary function of wetlands that in a natural state can prevent flooding of downstream landscapes. As wetlands are filled in by development activities, they no longer serve this function and can cause flash flooding conditions in regions were they have been removed. In addition, wetlands have been noted to remove NPSP pollutants by storing stormwater runoff. During this storage period, the plants and soils in the wetlands allow for the stormwater to filter into the groundwater system, effectively cleaning the NPSP out of the stored water through natural infiltration processes (Brinson, 1993; Fink and Mitsch, 2004). Fink and Mitsch (2004) suggest that this process is most effective when wetlands are located in the headwaters of rivers or as fringe wetland systems located adjacent to rivers and other receiving surface water systems. Like wetland systems, riparian habitats (i.e. vegetated buffer zones and wetlands) have been noted to remove nutrients (including P and N) from water traversing from landscapes, through these zones en route to stream and river systems. Sedimentation, soil absorption and plant uptake have been cited as the most important mechanisms for removal of nutrients (i.e. nitrogen and phosphorus) in riparian habitats. However, the capacity of riparian wetlands to remove nutrients may vary. Some studies have argued that riparian wetlands can remove up to 30 percent of the total nitrogen and phosphorus load.

In a study conducted in the Mississippi River Basin, Mitsch et al. (2001) calculated that 20 percent to 50 percent of total nitrogen load carried by the river could be removed by restoring a majority of riparian zones and wetlands associated with lower order streams. In addition, bottomland hardwood forest covering 3 percent to 5 percent of the entire basin could remove an additional 20 percent to 50 percent of the load. Mitsch et al. (2001) noted that other studies have indicated that nitrogen removal would require a riparian wetland area covering 5 percent of the total catchment. Critical loading (i.e. the loading rate below which the system remains unchanged) has been used as an indicator of the extent of nutrient loading a specific wetland system can incorporate without diminishing its ecological function. When loading rates exceed the critical level, species composition and ecosystem functioning change dramatically over a short period of time and the system often adapts to a different stable state. Such shifts have prompted scientists to propose critical loads for nitrogen and phosphorus for specific ecosystems. It has been noted that proposed critical loading rates of nitrogen and phosphorus for riparian wetlands are typically several magnitudes lower than constructed wetlands used for water quality improvement. Although wetlands in a catchment dominated by agricultural land can contribute to improved water quality, their loading rates often surpass critical values. According to the study, measurements from around the world have indicated that at least 2 percent to 7 percent of the total catchment needs to be in wetland habitat to see a significant improvement in water quality at the catchment scale. Other effects of excessive loadings into wetlands include significant increases in N2O emissions. Mitsch et al. (2001) conclude that riparian wetland systems and zones are key to improving water quality, but management of these systems to ensure they are functional requires loading rates to remain below critical thresholds. In many agricultural catchments, this would require a reduction in nutrient loadings to wetland systems (Mitsch et al., 2001).

Riparian Forest Buffers

Newbold et al. (2010) monitored water quality responses in a three-zone riparian forest buffer system (RFBS) over 15 years in the Piedmont region of Pennsylvania. The study examined ground and surface water quality for three watersheds including a RFBS, a reforested watershed, and a "control" watershed that remained in agricultural production. The three zones of the RFBS included a streamside strip of woody vegetated habitat; an 18 to 20m wide strip of reforested hardwoods upslope from the zone; and a 6 to 10m grass swale that captured surface runoff from an adjacent cultivated field.

Results indicate that nitrate concentrations downstream of the RFBS did not change initially, but showed significant reduction once vegetation was established in the reforested hardwoods. Groundwater samples taken from the reforested watershed and the grass swale showed significant nitrate concentrations in the first 3 years of the study indicating a lag time between previous surface nitrate applications and the ability of groundwater systems to filter nitrates. The study concluded that a 35m-wide RFBS could be efficient in removing 26 percent of subsurface nitrate flux and 43 percent of suspended solids from upslope sources; however, the RFBS was not effective in removing total phosphorus downstream (Newbold et. al., 2010).

As forestland, wetlands, and riparian areas continue to be reduced due to development, it will become increasingly important to understand how conserving and even re-establishing these systems could improve water quality at both the local and regional hydrological scales. Several studies (Newbold et al., 2010; Verhoeven et al., 2006; Binkley et al., 1999; Megahan & King, 1985) have demonstrated that these systems can be effective in removing NPSP for overland flow and stormwater runoff. Mitsch et al. (2001) stresses that these systems are only effective when their critical loads are not exceeded. Exceeding this load can result in the systems not only being overloaded with contaminants that degrade the habitat and water quality, but they can also increase greenhouse emissions. Carleton et al. (2000) note that reconstructed wetlands may be effective in removing NPSP, however, when compared to natural systems they are less effective in removing high concentrations of NPSP. This further illustrates the need to protect natural areas in and effort to protect water resources and related habitats at the local and regional geographic scales.

Land-Use/Land-Cover Changes, Landscape Gradients, and Watershed Characteristics

Beyond water quality varying based on individual land-use/land-cover (LULC) type, it is likely that variations or changes in LULC types may also cause significant impacts to water quality and aquatic ecosystems. Alterations of the landscape may include changes in the patterns in which surface runoff enters rivers and streams as well as the type and amount of NPSP entering these systems. In addition, changes in land types can create landscape gradients where one land type transitions into another type over small and large spatial extents. As these transitions or gradients occur, various landscape characteristics, such as increases in impervious surfaces, can be introduced to subbasins where they were previously not present. Wilson and Weng (2010) suggest that changes in land types such as increases in the amount of urbanization within a watershed can significantly affect the spatial and temporal patterns of stormwater runoff. Over time, this process permanently alters the hydrology of a watershed at the surface and sub-surface or groundwater scales. In addition, the extent of landscape changes within a given watershed heavily depends on the spatial-temporal variations in areas that contribute runoff as well as the spatial extent to which changes in the landscape take place. Other considerations that may drive these landscape alterations may include population growth, climate change, and various socioeconomic conditions and preferences (e.g. location of housing, commercial development, parks).

Land-Use/Land-Cover Changes and Water Quality

Land-use/land-cover (LULC) changes may alter the natural hydrological conditions of a watershed, the amount and spatial extent of land types and their proximity to surface water systems as well as the mechanisms in which NPSP enter river and stream systems. Carpenter et al. (2007) suggested that these changes will vary in nature, pattern, and pace causing ecological and societal consequences that will vary by spatial scales. This occurs as a result of economic and political pressures and sensitivity to environmental conditions at the local and regional scales.

Rothenberger et al. (2009) used land-use/land-cover (LULC) trends to determine surface water quality and landscape changes in the Neuse River Basin, North Carolina from 1992 to 2001. Land-use/land-cover practices in the lower portions of the Neuse River Basin represent approximately 70 percent of the state's swine CAFOs, while the upper portions of the basin represent mixed landscape patterns. The study used GIS to characterize 26 subbasins throughout the river basin and analyze changes in LULC that took into consideration urban, agriculture (CAFOS), industrial, forest, grassland, and wetland LULC categories. Results indicated that there were no significant differences in nutrient concentrations between basin regions, but the regions did differ in their relationships between nutrients and land types. Overall, sub-basins in the upper Neuse River Basin had higher urban and forested land cover and higher densities of industrial uses. The percentages of land cover for agriculture, wetlands, and CAFOs densities were higher in the lower portions of the basin. Comparisons of the 1992 and 2001 USGS LULC imagery exposed that total urban land cover in the Neuse River Basin increased from 5 percent to 16 percent, with urban sprawl occurring near the cities of Raleigh/Durham, Wilson, Goldsboro and New Bern. Coinciding with the increase in suburban land cover was a 21 percent increase in human population, a 30 percent increase in wastewater treatment plants, and a 324 percent increase in meat packaging plants. Water quality parameters showed significant changes related to climatic and landscape changes. For example, during the summer total phosphorus concentrations were higher in subbasins with a high density of WWTPs and CAFOs. In contrast, nitrate was significantly higher during the winter in subbasins characterized by a high number of WWTPs and organic nitrogen was higher in subbasins with high percentages of agricultural practices including pastures fertilized with animal manure. In addition, ammonia concentrations were elevated after high precipitation in this watershed.

Rothenberger et al. (2009) concluded that wastewater discharges (point sources) in the upper basin and swine CAFOs (non-point sources) in the lower basin were the highest contributors of nitrogen and phosphorus to receiving surface waters. The study also suggested that future research is needed to support sustainable land management practices to control non-point sources of pollution in this watershed, and argued that when sufficient monitoring data are available, their empirical approach provides a powerful tool to address watershed management issues (Rothenberger et al., 2009).

Landscape Gradients

Landscape gradients may exist due to natural features in the landscape such as geological, climatic, and topographical changes as well as anthropocentric changes to the landscape that may be driven by socioeconomic choices. Gradients may include forest land being converted to agricultural or urban areas or as more recent trends suggest, agricultural land being converted to urban areas (Schoonover et al., 2005; Grimm et al., 2008; Wear et al., 1998; and others). Grimm et al. (2008) notes that when considering urban form, various types of landscape gradients radiate from urban cores from both small and large cities. Since these variations exist, it is important to look beyond individual case studies in an effort to identify these gradients and their ecological impacts across a wider spatial continuum. Understanding these characteristics and changes throughout a river basin is important in the analysis of water quality data because they impact the chemical, physical and biological components of the samples under investigation.

In the Cape Fear River Basin a natural landscape gradient exists from the headwaters in the piedmont region of North Carolina to the mouth of the basin in the coastal region, which is characterized by blackwater streams, peatlands, and tidal creek systems (NC WRC, 2013). In addition to this natural gradient, an anthropocentric gradient of different land-types exists including a transition from urban to rural and forested land (NC DENR, 2005). When considering water quality in this river basin, the pH in the lower basin is typically lower in the lower portion of the basin when compared to the upper portions due to the natural characteristics of blackwater systems. These gradients further illustrate that both natural and anthropocentric gradients must be taken into consideration when analyzing water quality across large heterogeneous landscapes.

When considering water quality changes along an urban-rural gradient, significant impacts may occur not only in water chemistry, but also to the ecosystem structure depending on the location within a given gradient (Wear et al., 1998). Schoonover et al. (2005) argues that a major impact of landscape gradients that transition from rural to urban development is an increase in impervious surfaces. The key question addressed in this study was the extent to which urbanization can affect the physical, chemical and biological aspects of stream health in the Piedmont physiographic province of Georgia. A two phase, watershed scale study was developed to observe relationships among land types and water quality along the rural-urban landscape gradient.

During the first phase of the study, streams ranged from first to third order streams, while the second phase of the study added additional watersheds to further test relationships between landscape gradients and water quality. Biweekly samples were taken and included biological, physical and nutrient water quality parameters during both the winter and spring seasons. Results indicate that on an annual basis stream discharge was significantly higher in urban streams than all other land types combined. When considering land types and nutrient loading the study found that as the percentage of forested land increased within a watershed, a negative correlation was found between all of the water quality parameters under investigation. Conversely, a strong positive correlation was indicated between the percent urban area and each of the water quality parameters. Thus, as the percentage of forest cover increased within a watershed, lower nutrient concentrations were observed. In contrast, as the percentage of urban and developed areas increased, concentrations of nutrient concentrations increased within the watershed. This relationship was directly linked to an increase in impervious surface cover above five percent in urban and developed areas. Schoonover et al. (2005) concluded that concentrations of water quality parameters were significantly higher in urban watersheds regardless if the streams were experiencing base or peak flow conditions.

Holland et al. (2004) used multiple landscape metrics and demographic attributes to characterized relationships between tidal creek ecosystems and water quality along a forest-urban landscape gradient. In their assessment of 23 headwater tidal creeks in South Carolina from 1994 to 2002, Holland et al. (2004) evaluated the following: (1) the degree to which impervious land cover is an integrative watershed-scale indicator of ecological stress, (2) analyzed the linkages that exist between land cover and environmental quality in response to human development, and (3) use the resulting models to develop recommendations for conserving and restoring tidal creek ecosystems. Specific parameters for evaluation included population density, land types, percent impervious cover, creek physical characteristics, sediment grain size, and water quality parameters including mean stream temperature and salinity, fecal coliform, pore water ammonia, dissolved oxygen (DO), and the amount of macro and nekton populations. Results indicate that when urban areas are present, population density was significantly associated with increases in impervious surfaces. In contrast, when considering industrial areas, human population was negatively correlated with the amount and extent of impervious surfaces. For example, an industrial site, such as a factory or shipyard, may have a large building footprint and related parking areas, however, the population only increases during peak production hours unlike residential areas where the population lives and thrives on a daily basis. Hypoxic conditions (i.e. dissolved oxygen values < 28 percent saturation) were found during the summer in forested and developed watersheds. The mean DO and the percent of time DO values were below the 28 percent critical value for sustaining aquatic life were not associated with the amount of impervious surface present in a given watershed. When considering the biological abundance of stress-sensitive macrobenthic taxa the upper and lower creek reaches were negatively associated with the amount of impervious surfaces in both the summer and winter months. This study supports the argument that there is a positive correlation between the amount of impervious surfaces and the amount of fecal coliform bacteria further indicating that impervious surfaces may serve as a conveyance system for NPSP to surface waters.

Holland et al. (2004) suggested that the ultimate stressor on the tidal creek ecosystem in this study was the presence of high population densities and associated increases in the amount of impervious land cover. As noted in previous studies (Mallin et al., 2001; Scheuler, 1994; Brabec, 2009; Arnold & Gibbons, 1996 and others) measurable adverse changes in the physical and chemical environment were observed when impervious surface cover exceeded 10-20 percent. Changes included an altered hydrograph (e.g. sharp increases in stormwater flow in short time periods), changes in salinity variance, altered sediment characteristics, increased chemical contaminants, and increases in fecal coliform loadings to surface waters. The findings in this study suggest that the amount of impervious surface within a watershed appears to be an integrative measure of the adverse human alterations to the landscape and future research should focus on the ecological implications of altering the landscape from forest cover to urban land (Holland et al., 2004).

Watershed Characteristics and Water Quality

Watershed characteristics may include the spatial distribution of populations, the mixture and patterns of the landscape as well as the spatial extent of impervious surfaces within a given study area. Mallin et al. (2001) observed that increases in coastal population and tourism have resulted in declines in water quality. The transition of increased human populations in coastal areas greatly increases the number of microbial pathogens and alters the landscape through increased construction activities and paving of natural areas. Mallin et al. (2001) investigated the relationships that exist between aquatic microbial pollution and population, landscape, and meteorological mechanisms from 1984 to 1997 in the lower Cape Fear River Basin. Fecal coliform bacterial samples were collected throughout New Hanover County tidal creek systems on a monthly basis at the same stations at or near high tide. Monthly freshwater fecal coliform samples from a series of sampling stations representing drainage from different rural watersheds located in the study region were also collected. Other data included the amount of shellfishing areas closed due to excessive fecal counts and coastal population data for Carteret, Onslow, Pender, New Hanover and Brunswick Counties.

Results illustrated that on a regional scale, increases in human populations were strongly correlated with increases in shellfish closures due to high fecal coliform counts. At the watershed scale, several tidal creeks were found to have strong correlations between mean estuarine fecal coliform bacterial counts and watershed population, percent developed area and percent impervious surface coverage. An analysis of rural watersheds in the Coastal Plain concluded that stream fecal coliform counts and turbidity were both strongly correlated with rainfall in the previous 24 hours in watersheds containing extensive industrial swine and poultry operations, as well as watersheds containing more traditional agriculture and cattle husbandry. In contrast, watersheds rich in swamp wetlands did not indicate significant relationships between watershed characteristics and water quality, even those containing animal operations. It is suspected that, in general, stormwater runoff from impervious surfaces is the major contributor of microbial pathogen pollution in this region. In addition, increases in human population leads to consequent increases in land development. In rural watersheds, watersheds with 13.8 percent wetlands coverage or greater appeared to be buffered against excessive turbidity and fecal coliform runoff after rain events. The study concluded that the loss of rural wetlands and conversion of natural landscapes to pollution-prone landscapes encourages microbial pollution of coastal plain streams (Mallin et al., 2001).

Cookson and Schorr (2009) examined of watershed housing density and instream environmental conditions and fish assemblage in a Tennessee ridge and valley stream. Watershed landscape patterns upstream of the site were delineated using 1998 satellite imagery provided by the Tennessee Valley Authority (TVA). Findings in this study suggested that stream water quality and habitat characteristics vary among study stream reaches. Watershed housing density was directly correlated with stream temperature, CV for discharge, sediment depth, introduced fish abundance, and tolerant fish abundance. In contrast, housing density was inversely correlated with dissolved oxygen, pH, CV for thalweg depth (i.e. the deepest part of the stream channel), substrate diversity, and native species richness. Other landscape-stream relationships were not found to be statistically significant ($p > 0.10$). Cookson and Schorr (2009) note the negative effects of residential development on stream water quality, hydrology, channel morphology, stream substrate and fish assemblages. Stream reaches draining residential catchments with greater housing densities exhibited warmer temperatures, reduced dissolved oxygen (DO) concentrations, slightly lower pH values, flashier discharges, more homogenous depths, less substrate diversity and increased sedimentation. Correlations with 2005 housing density with certain physicochemical parameters suggest that declines in water quality may occur with increased development in the Mountain Creek systems despite the fact that observations in this study were compliant with state water quality standards. Cookson and Schorr (2009) suggest that future research of urban-suburban catchments that exhibit trends towards residential development should evaluate the utility of housing density as a landscape predictor of stream conditions.

Land-use/land-cover changes, landscape gradients and watershed characteristics can have a profound influence on water quality within a given watershed. Land-use/land-cover changes and gradients can result in new landscape features that produce different types and amounts of NPSP inputs to surface waters as illustrated by Rothenberger et al. (2009) and Grimm et al. (2008). When considering landscape gradients, Grimm et al. (2008) make an important point that case studies are ineffective in capturing the ecological impacts these transitional landscapes have across a wider spatial continuum. Watershed characteristics such as the spatial distribution of populations and housing densities can influence concentrations of NPSP entering surface waters. Mallin et al. (2001) note that an increase in watershed population can increase the amount of fecal coliform entering stream systems and may drive more dispersed impervious surface patterns. Cookson and Schorr (2009) suggest that residential development can impact not only stream water quality, but also stream hydrology, channel morphology, substrate and fish assemblages. As illustrated by these studies, understanding the characteristics that define watershed are important indicators of stream and aquatic ecosystem health.

Linking Land-Use/Land-Cover Types to Water Quality

Regional Water Quality Monitoring

Assessing water quality on a regional scale can be useful in viewing trends; however, methods for assessment are difficult because landscapes over large spatial extents are typically heterogeneous in nature (Qui & Prato, 1999; Schwabe, 2001; Smith et al., 1997). Smith et al.

(1997) describe the complex nature of assessing water quality on a regional basis. Specific barriers to assessment include the spatial distribution of monitoring stations due to cost, location of monitoring stations in response to the need to identify specific pollutant sources, and land heterogeneity. The objective of that study was to develop a method for interpreting monitoring data in an effort to identify portions of watersheds with outflows of total phosphorus (TP) less than the national criteria and to classify total nitrogen (TN) yields units according to local TN standards. In their assessment, Smith et al. (1997) incorporated a Spatially Referenced Regressions on Watershed (SPARROW) model to assess regional water quality. SPARROW is designed to reduce problems associated with data interpretation caused by diffused sampling, network bias, and basin heterogeneity. From this model, Smith et, al. (1997) employed regression models for TP and TN transport for the non-tidal conterminous United States. Water quality records for 414 stations in the National Stream Quality Accounting Network were observed for TN and TP transport rates. Construction of the regression models for TP and TN were developed using the mathematical watershed model, SPARROW, and incorporating the digital stream River Reach Network, which contains numerous scenarios of stream diversion and stream braiding. The models captured additional data sources, such as the type of contamination sources and land and surface characteristics, as well as accounting for in-stream measurements in relation to basin attributes.

Smith et al. (1997) observed that the application of the TP and TN models illustrated the model's potential to oversimplify transport processes, which limits its ability to provide specific resource information. Results demonstrated that the spatial reference of in-stream measurements in relation to basin attributes greatly increase the precision and descriptive potential of regression-based water-quality models (Smith et al., 1997). The SPARROW method was successful in supporting TP and TN regression model applications. By estimating the TP exceedance proportions from SPARROW, a regional model can be consistently replicated for application in state and local planning as well as education and outreach activities. This study suggested that future research should apply SPARROW in water quality sampling and network design in an effort to simulate the effects of changes in sampling locations and sampling frequency on the reliability of water quality monitoring data.

Watershed-Scale Modeling for Predicting Non-Point Pollution Risk

Modeling the potential impacts to surface waters from various LULC types has become increasingly important to avoid impairments before they occur. Potter et al. (2004) applied an ecological risk assessment framework to develop and analyze vulnerability models that can be used to illustrate how landscape changes may impact surface water quality in North Carolina. Geographic Information Systems (GIS) databases were used to examine landscape characteristics for 73 watersheds throughout North Carolina as well as the riparian zones (100 ft) located along both sides of the streams within each of the watersheds under investigation. The overall objectives of this study were to (1) investigate the importance of land cover on the health of benthic macroinvertebrate community composition and (2) to develop vulnerability models to assist policymakers and natural resource managers in developing more comprehensive understand of how land cover changes impact surface water quality in North Carolina watersheds.

Variables used in the analysis of stream invertebrate tolerance to stream degradation include the following: macroinvertebrate index scores (response), land cover (predictor), precipitation (predictor), watershed area (predictor), watershed shape index (predictor), watershed slope/relief ratio (predictor), topographic complexity (predictor), mean elevation (predictor), and clay content of soil (predictor). The macroinvertebrate index score included two different biological indices. The first index, the North Carolina Biotic Index (NCBI), was developed to examine the general level of pollution at stream sites by rating stream based on the water quality tolerance of the macroinvertebrates samples at a given site. The second index, the Ephemeroptera (i.e. mayfly), Plecoptera (i.e. stonefly), and Trichoptera (i.e. caddisfly) tolerance (EPTBI) index, is restricted to the three invertebrate taxa considered highly sensitive to water quality degradation. Data analysis included a series of simple linear regression models to examine the direction and strength of association between the landscape variables and the biological indices. An addition statistical analysis included a multiple regression model aimed at observing the proportion of variability in the stream invertebrate tolerance indices attributed to the most statistically significant landform and land cover variables at the watershed scale.

The simple regression analysis demonstrated statistically significant relationships between several landscape variables and the NCBI and EPTBI indices. Exceptions included the percent riparian zones developed, watershed area, watershed shape, and soil clay content. Percent agricultural land cover had a positive relationship with both indices, meaning that it was negatively correlated with aquatic macroinvertebrate integrity (i.e. poor stream health). Conversely, the percent forested land cover was correlated with healthy stream conditions. It was also noted that as the amount of precipitation increased it is likely that surface water quality and aquatic habitat conditions may be improved. This could be contributed to a general dilution effect that weakens the concentration of NPSP as the amount of rainfall increases. Potter et al. (2004) concluded that land cover in North Carolina is a significant predictor of aquatic macroinvertebrate tolerance, which can serve as a viable indicator of water quality health. It is argued that this model could assist policymakers and natural resource management agencies in determining how land cover changes can result in impaired water quality throughout North Carolina. Understanding these impacts could result in the development and implementation of policies and practices that aim to reduce impacts to water quality and related macroinvertebrate communities.

Water Quality Monitoring by Satellite Imagery and GIS Applications

Satellite imagery and Geographic Information Systems (GIS) have been used to identify landscapes that may contribute to poor water quality (Carle et al., 2005; Dougherty et al., 2004; Usali & Ismail, 2010). In their review of various methods of monitoring water quality using satellite imagery, Usali and Ismail (2010) analyzed various applications of remote sensing and GIS techniques in monitoring water quality parameters, including suspended matter, phytoplankton, turbidity, and dissolved organic matter in Malaysia. The study categorized water quality parameters, including the following: (1) Biological: bacteria, algae; (2) Physical: temperature, turbidity and clarity, color, salinity, suspended solids, dissolved solids; (3) Chemical: pH, dissolved oxygen, biological oxygen demand, nutrients, organic and inorganic compounds and (4) Aesthetic: odors, taints, color and floating matters.

Usali and Ismail (2010) note that several studies have shown that a significant relationship exists between suspended matter and radiance (i.e. image pixels) from either a single band or a combination of bands of wavelength reflectance (i.e. image data captured by the electromagnetic spectrum) from the satellite. The satellite reflectance wavelength between 700nm and 800nm and Landsat imagery in general were the most useful tools in determining suspended matter in surface water bodies. When measuring phytoplankton in surface waters, Usali and Ismail (2010) note that Landsat, SPOT, SeaWiFS and CZCS satellites use various algorithms and wavelengths that were helpful in determining and mapping chlorophyll in a variety of water bodies. Usali and Ismail (2010) conclude that these satellites can assist researchers in indentifying water quality parameters that may contribute to impaired water quality.

Recent Applications in Geography

Historically, the geography literature is not extensive regarding the analysis of changes in landscape patterns and water quality over large spatial extents. A few recent studies (Tu, 2011; Tu et al., 2007; Su et al., 2012) have applied geographically weighted regression (GWR) to identify changes in land patterns over large heterogeneous landscapes (e.g. Su et al., 2012) as well as relationship between land types and water quality (e.g. Tu, 2001; Tu et al., 2007) in a geographical context. Typically, ordinary least squares (OLS) and Spearman's rank correlation statistical analysis are used to study associations and correlations related to landscape changes and relationships between LULC types and water quality over heterogeneous landscapes. Both Su et al. (2012) and Tu (2011) note that using this statistical approach assumes that the entire study area is homogenous and in doing so local variation (e.g. land types, high and low-density development) are not taken into consideration. Additionally, Su et al. (2012) notes that OLS lacks the ability to uncover some local-specific relationships and spatial autocorrelation inherent in model residuals, which can result in false interpretations of the models.

In a study of the Boston metropolitan area, Tu (2011) explored how relationships between six LULC types (forest, agricultural, commercial, industrial, recreation use, and residential) and 14 water quality indicators (specific conductance (SC), dissolved solids, six dissolved ion indicators and six dissolved nutrient parameters) change over space in response to varying levels of urbanization within a watershed. Using water quality indicators as the dependent variables and land types as the independent variables, 84 GWR models were developed in an effort to illustrate and explain the influence, extent and spatial variability a single LULC type has on a given water quality indicator. Specific conduction (SC), dissolved ions and solids, and dissolved nitrogen parameters were significantly associated with most of the landscape indicators including percentage of agricultural, forest, commercial, industrial, residential, and recreational lands. It was noted that although this was the general trend across the entire study site, the degree of association varied spatially among individual water quality parameters and landscape indicators when observing specific sampling points. This finding demonstrates that relationships between the dependent and independent variables were not constant throughout the study area. Tu (2011) concluded that the adverse impact of land types on water quality is more substantial in less urbanized areas than in highly urbanized areas. This was statistically illustrated by (1) the stronger positive relationships between concentrations of water pollutants and percentages of commercial and industrial lands in less-urbanized watersheds than those in highly-urbanized watersheds, and (2) the significant positive relationships with percentages of agricultural land, residential land, and recreation use observed at some site within less-urbanized areas in contrast to the significant negative relationships for them found in highly-urbanized areas.

Although Su et al. (2012) only considered landscape changes in their application of GWR, it is an important study to note because the study site (i.e. 26,333 km^2) is similar in size to the Cape Fear River Basin (i.e. 24,086 km^2). In addition, the study showcases how GWR can be an effective tool in assessing LULC changes both spatially and temporally over a large heterogeneous landscape. Su et al. (2012) applied GWR analysis in an effort to examine spatially varying relationships between several urbanization indicators (i.e. urbanization intensity index, distance to urban centers and distance of road) and changes in metrics describing agricultural landscape patterns (i.e. total area, patch density, perimeter area ratio distribution and aggregation index) in the Hang-Jia-Hu region of coastal China from 1994 to 2003. A gradient in terrain exists within the study area including flat agricultural land-types in the northeast to steep forested land cover in the southwest with urban areas interlaced between these two regions.

Data analyzed included LULC images for 1994 and 2003 obtain from the Landsat TM satellite and three urbanization indicators were selected including an urbanization intensity index, distance to road and distance to urban center. GWR was applied to extend OLS in an effort to identify the spatial varying relationships by generating a set of local-specific coefficients, including local R^2, local model residuals, local parameter estimates as well as the corresponding t-test. Results indicate that considerable urbanization was identified across the whole region with urban centers having more intense urbanization and the northeastern part of the study area experiencing more significant urban expansion. Agricultural land changes included a decline in total area and more fragmented density of agricultural land verses a continuum of agricultural land types across the study region that was present in 1994. When comparing GWR to OLS, Su et al. (2012) suggest that GWR models are superior in explaining the relationships between agricultural landscape patterns and urbanization. In addition, it is argued that GWR exhibits stronger explanatory power in regions where a heterogeneous landscape gradient is present. It is argued that GWR still presents some disadvantages despite its wide acceptance as an effective spatial statistical tool. Primary disadvantages include the following: (1) the lack of independence among local estimates may lead to the failure in valid inferences for the local estimates, (2) the presence of outliers may result in inappropriate local coefficients, and (3) when the number of sample is quite small, the estimated local coefficients can be ineffective or invalid as well as suffering multicollinearity issues.

Contributions to the Literature

This dissertation seeks to add to the growing literature that examines the relationships that exist between land types and water quality by identifying, quantifying and spatially illustrating these interactions throughout the Cape Fear River Basin, North Carolina from 2001 to 2006. As noted by the extensive literature review presented above, there are significant, but varying, relationships between land types and the types and amounts of NPSP that enter surface water systems at the local and regional geographical scales. Although research in the Cape Fear River Basin has demonstrated that some relationships exists between land types and water quality, the studies tend to overlook relationships between the landscape and water quality over large heterogeneous landscapes and the extent to which spatial and temporal changes influence surface water quality. Multiple disciplines have approached this topic using a variety of methods. For example, Rothenberger et al. (2009) used classified LULC imagery as well as water quality data for both point and non-point sources of pollution to determine relationships between land types and water quality throughout the Neuse River Basin, North Carolina. However, the statistical method applied, OLS, did not take into consideration local variability within the study area such as differences in land-use policies (i.e. minimum lot size, number of dwelling units/per acre), climatic influences and development trends and how these characteristics influence water quality across a heterogeneous landscape.

Su et al.'s (2012) application of GWR to urban and agricultural landscape metrics assisted the researchers in demonstrating that GWR is a strong tool in spatially and statistically showcasing how landscape patterns change over a large heterogeneous landscape. Although it was argued that GWR was a more powerful tool in assessing these changes overtime, it did not investigate how these landscape patterns and types influence water quality throughout the study area. As illustrated by Tu (2011) GWR is a viable statistical method that can be used to identify and quantify the impacts of landscape changes on surface water quality. Tu's (2011) application of GWR contributed to the growing literature that seeks to understand relationships between LULC and water quality by suggesting that GWR is a viable statistical technique that can be applied across heterogeneous landscapes. One of the primary weaknesses of Tu's (2011) analysis is that it misses a critical opportunity to apply the primary feature of GWR, its ability to analyze multiple variables while changing local coefficients in the regression model, by only addressing how one land type influences a single water quality parameter at a given location. In addition, several studies have argued that GWR needs to be applied with caution when using less than 100 samples in a dataset to avoid generating coefficients that misrepresent relationships between the dependent and independent variables. By enhancing the methods applied by Rothenberger et al. (2009), Tu (2011), and Su at al. (2012) a research blueprint can be established that could be applied to other research efforts that seek to identify and explain spatial-temporal relationships between landscapes and water quality across heterogeneous landscapes.

CHAPTER III

METHODS

As the population of the Cape Fear River Basin continues to increase, there will be a mounting need to address how this growth will impact the land-use/land-cover (LULC) patterns and surface water quality and quantity. As the literature reviewed has demonstrated through various disciplines, increases in population results in the development of various land patterns including low and high-density development as well as various LULC types (e.g. residential, industrial, agricultural, and commercial development) needed to support the population both physically and economically. During the development process, land patterns transition from one type of use to another resulting in numerous levels and types of adverse impacts to surface water systems. The impairment of surface water quality from anthropocentric activities reduces the quantity and quality of surface water resources needed for drinking water, industrial uses, and irrigation for agricultural practices. In addition, this process changes the morphology of stream and river systems resulting in short and long-term degradation of natural ecosystems. Given the unique natural resources inherent within the Cape Fear River Basin, it is vital to identify relationships between LULC and water quality in an effort to alleviate short-term and long-term impacts to surface water systems. In doing so, a research framework could be developed that may be applied to other river basins which seek to mitigate impacts to surface water quality.

Research Questions

Understanding relationships between the landscape and water quality is an important factor in developing watershed assessment tools and land-use policies that protect surface water resources. This dissertation seeks to add to the growing body of literature related to LULC and water quality by exploring the following research questions:

(Q1) To what extent and how do changes in LULC types influence surface water quality at the river basin scale in the Cape Fear River Basin?

Several studies (Binkley et al., 1999; Potter et al., 2004; Megahan & King, 1985; and others) have noted that forested landscapes typically exhibit a negative correlation with pollution inputs in surface water systems. This is due to many of the characteristics inherent within forested landscapes, such as vegetative cover, which allow for transpiration and natural infiltration processes, and little to no impervious surfaces (e.g. sidewalks, streets, buildings). It is anticipated that increases in forested land will support better water quality when compared to increases in urban areas. This is anticipated because the landscape features associated with urban development (i.e. impervious surfaces, stormwater systems, WWTPs), will result in an increase in pollutant concentrations entering surface water systems.

In contrast, agricultural land types typically contribute some level of pollution to surface waters resulting in degraded water quality. Given that pollution is already present in these stream systems, there will not be a drastic change in water quality as agricultural landscapes transition to urban landscapes. This trend is anticipated because both landscapes are associated with some level of pollution inputs in surface water systems. It is expected that water quality will begin to exhibit a noticeable change as development activities increase across the river basin and at the physiographic region scales. This occurs primarily because impervious surfaces can serve as an efficient conveyance system for pollutants to reach river and stream systems than overland runoff from agricultural landscapes.

(Q2) To what extent do developed LULC types influence surface water quality at the river basin scale and across different physiographic regions?

As Tu (2011), Mallin et al. (2000), Hatt et al. (2004), and others have illustrated, less-urbanized areas (i.e. areas with < 50% impervious surfaces) may cover a larger spatial extent and vary drastically in the amount of land types when compared to higher intensity urban development (i.e. >50% impervious surface). Less-urbanized areas may include more dispersed impervious surfaces such as extensive road networks, which may contribute more to impaired surface water systems across the river basin. As a result, it is likely that less-urbanized areas will exhibit poorer water quality when compared to highly urbanized areas.

(Q3) To what extent do agricultural LULC types influence surface water quality at the river basin scale and across different physiographic regions?

As noted by Zhu (2012), in agricultural settings the amount and type of pollution inputs may be attributed to different agricultural practices (e.g. crop vs. livestock) in addition to seasonal activities (e.g. crop planting, harvesting, and nutrient applications). As a result it is anticipated that pollutants entering stream and river systems in physiographic regions dominated by agricultural land types (>50%) will exhibit variability in the amount of pollutant concentrations. In addition, several studies have observed significant concentrations of pollutants from CAFOs when compared to traditional agricultural activities. Given this finding, it is anticipated that monitoring stations draining landscape that contain CAFOs will exhibit poorer water quality when compared to those draining traditional agricultural practices.

Study Site

The Cape Fear River Basin (CFRB) is North Carolina's largest river basin that is completely contained within the state's borders and includes three physiographic regions, six subbasins (i.e. USGS 8-digit hydrologic unit code), and 44 watersheds (i.e. USGS 10 digit hydrologic unit code). The river basin's geographical boundary begins in the north central piedmont near Greensboro and extends southeast through the coastal plain to the Atlantic Ocean near Wilmington (Figures 1a and1b). The Cape Fear River itself is approximately 200 miles and begins in Chatham County at the confluence of the Haw and Deep Rivers (DENR, 2000).

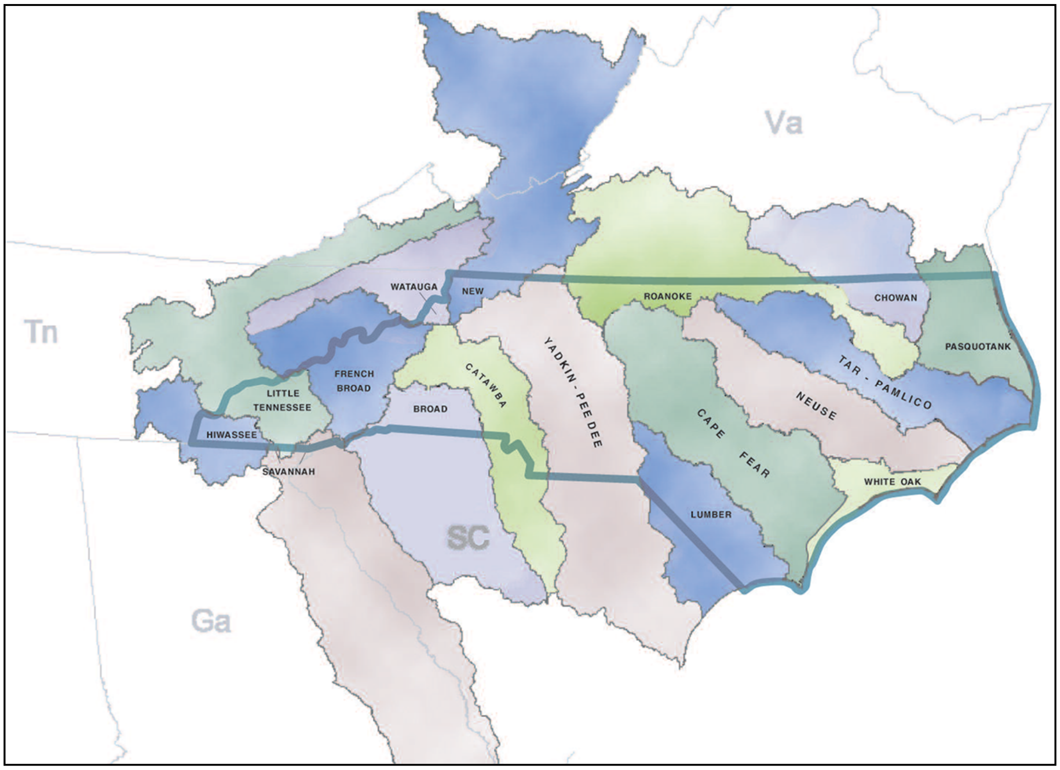

Figure 1a. North Carolina River Basins.
Source: NC DENR Office of Environmental Education (2012)

The basin is divided into three physiographic regions: the Upper (UCFRB), Middle (MCFRB) and Lower (LCFRB), each with distinct geological, topographical, biological and climatic characteristics (Figure 1b). The basin also encompasses different aquatic ecosystems, including woody and emergent wetlands, blackwater systems and fresh and salt water estuaries that provide wildlife habitat for over 30 endangered species as well as recreational opportunities for residents and visitors alike. In addition, the basin provides water resources for residential, commercial, and industrial uses (USGS a, 2012; NC DENR, 2005).

Each region of the basin embodies a variety of different land types, including urban, agricultural, and industrial uses, and geological regions including the piedmont, sandhills, and coastal plains that contribute to point and non-point sources of surface water pollution. The UCFRB (i.e. subbasins 03030002 and 03030003) is characterized by the piedmont region of North Carolina, traversing 12 counties including portions of Rockingham, Caswell, Guilford, Alamance, Orange, Durham, Wake, Chatham, Randolph, Moore, Montgomery, and Lee. The MCFRB (i.e. subbasins 03030004 and portions of 03030005) is largely considered the sandhills region of North Carolina traversing portions of Wake, Less, Moore, Harnett, Hoke, Cumberland, Bladen, and Columbus counties. The LCFRB (i.e. portions of 03030005, 03030006 and 03030007) is characterized by the coastal plain of North Carolina and includes portions of Johnston, Wayne, Lenoir, Bladen, Brunswick, and Onslow counties and a vast majority of Sampson, Pender and New Hanover counties.

This basin is the most industralized river basin in North Carolina, with 280 permitted municipal and industrial wastewater dischargers contributing point source inputs to its surface waters (DENR, 2005).

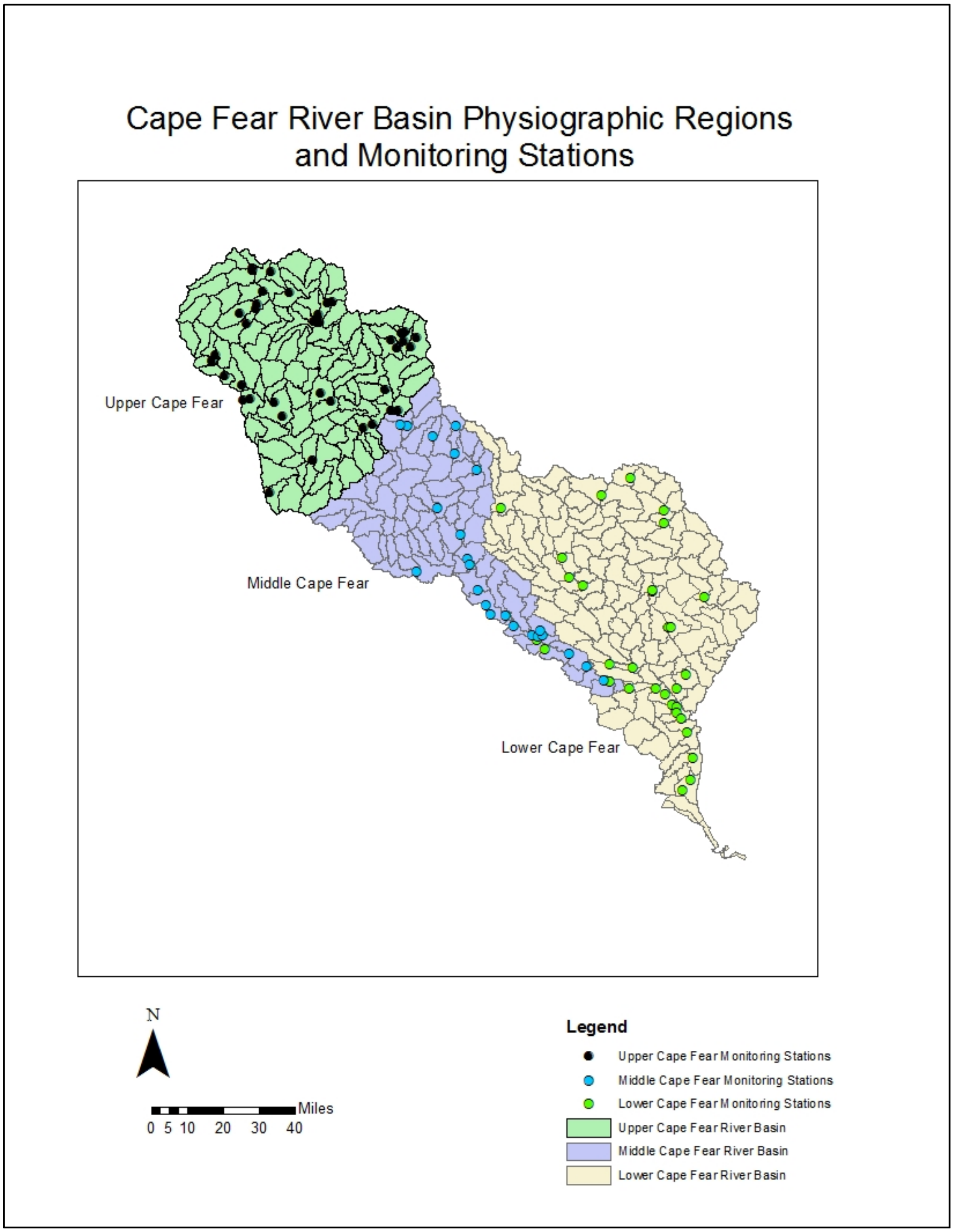

Figure 1b. Cape Fear River Physiographic Regions and Water Quality Monitoring Stations.

Point source pollution activities in the basin are permitted by the NC DENR and through the federal National Pollution Discharge Elimination System (NPDES) and include industrial and concentrated animal feeding operations (CAFOs) such as swine and turkey operation activities (Figure 2). There are over 300 miles of impaired streams located within the Cape Fear River Basin. These impaired streams have been linked to urban, agricultural, and industrial activities. The Triad and Triangle area cities and Fayetteville are the most densely populated areas located within the basin. The 26 counties located within the basin are expected to see an estimated 28 percent increase in population over the next 20 years, with most of this increase occurring in urban or urbanizing areas (NC DENR, 2005; Mallin, 2012). As the Cape Fear River Basin continues to experience additional population growth and related development, it will become increasingly important to understand how land types, spatial patterns, and related policies affect local and regional water quality.

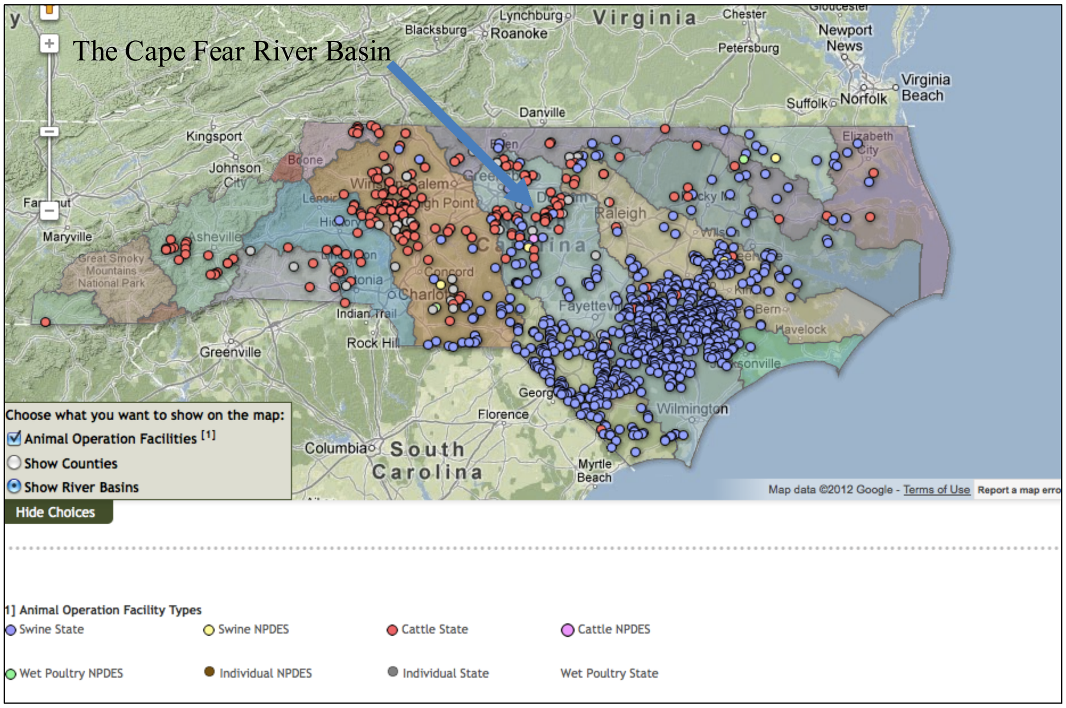

Figure 2. Permitted Point Source and Animal Operation Facilities by River Basin in NC. Source: NC DENR Division of Water Quality (2012)

Land-Use/Land-Cover (LULC) Assessment

In an effort to illustrate LULC changes across the Cape Fear River Basin (CFRB) as well as within each physiographic region, National Land Cover Database (NLCD) imagery for 2001 and 2006 will be downloaded from the Department of Agriculture's geospatial database and imported into ArcGIS 10 (USGS, 2012a). This imagery has a 30m resolution and is classified into Anderson II LULC categories including agricultural (e.g. hay/pasture and cultivated crops) and urban (low, medium and high intensity development) land types. Each LULC type has its own classification description and a distinct color assigned to their classification type (Figure 3). It should be noted that some of the LULC classifications do not apply to the study area (i.e. sedge/herbaceous, lichens, moss, dwarf scrub, and perennial ice/snow) so they will be excluded from this analysis. This will result in the inclusion of 14 LULC classifications including the following: developed open space, developed low intensity, developed medium intensity, developed high intensity, barren land, deciduous forest, evergreen forest, mixed forest, shrub/scrub land, herbaceous grassland, hay/pasture, cultivated crops, woody wetlands, and emergent herbaceous wetlands. Descriptions for developed areas include percent impervious surface, which will assist in understanding the extent of developed landscape patterns. For example, developed, open space has impervious surfaces that account for less than 20 percent of the total land cover, while developed, high intensity has impervious surfaces that cover 80 to 100 percent of the total land cover. It should be noted that the term "Open Space Development" could lead one to interpret this LULC type as green spaces filled with vegetated land types including parks, forest land, and golf courses. In an effort to more accurately represent this LULC type this study will reference this LULC type as "Exurban Development". This term was selected because this LULC category includes a mixture of developed and transitional land typically found along the suburban-rural continuum, which may include large-lot single family homes (e.g. McMansions) with large grass lawns, undeveloped green space, recreational areas, and dispersed road networks. Percentages of each LULC across the basin as well as within a given physiographic region will be calculated using ArcGIS 10, which is determined by calculating the total number of pixels of a given land type in a defined area divided by the total pixels of all LULC categories. This calculation will then be converted and reported as the percent square kilometer of a given land type.

Class\Value	Classification Description
Water	
11	Open Water - areas of open water, generally with less than 25% cover of vegetation or soil.
12	Perennial Ice/Snow - areas characterized by a perennial cover of ice and/or snow, generally greater than 25% of total cover.
Developed	
21	Developed, Open Space - areas with a mixture of some constructed materials, but mostly vegetation in the form of lawn grasses. Impervious surfaces account for less than 20% of total cover. These areas most commonly include large-lot single-family housing units, parks, golf courses, and vegetation planted in developed settings for recreation, erosion control, or aesthetic purposes.
22	Developed, Low Intensity - areas with a mixture of constructed materials and vegetation. Impervious surfaces account for 20% to 49% percent of total cover. These areas most commonly include single-family housing units.
23	Developed, Medium Intensity – areas with a mixture of constructed materials and vegetation. Impervious surfaces account for 50% to 79% of the total cover. These areas most commonly include single-family housing units.
24	Developed High Intensity -highly developed areas where people reside or work in high numbers. Examples include apartment complexes, row houses and commercial/industrial. Impervious surfaces account for 80% to 100% of the total cover.
Barren	
31	Barren Land (Rock/Sand/Clay) - areas of bedrock, desert pavement, scarps, talus, slides, volcanic material, glacial debris, sand dunes, strip mines, gravel pits and other accumulations of earthen material. Generally, vegetation accounts for less than 15% of total cover.
Forest	
41	Deciduous Forest - areas dominated by trees generally greater than 5 meters tall, and greater than 20% of total vegetation cover. More than 75% of the tree species shed foliage simultaneously in response to seasonal change.
42	Evergreen Forest - areas dominated by trees generally greater than 5 meters tall, and greater than 20% of total vegetation cover. More than 75% of the tree species maintain their leaves all year. Canopy is never without green foliage.
43	Mixed Forest - areas dominated by trees generally greater than 5 meters tall, and greater than 20% of total vegetation cover. Neither deciduous nor evergreen species are greater than 75% of total tree cover.
Shrubland	
51	Dwarf Scrub - Alaska only areas dominated by shrubs less than 20 centimeters tall with shrub canopy typically greater than 20% of total vegetation. This type is often co-associated with grasses, sedges, herbs, and non-vascular vegetation.
52	Shrub/Scrub - areas dominated by shrubs; less than 5 meters tall with shrub canopy typically greater than 20% of total vegetation. This class includes true shrubs, young trees in an early successional stage or trees stunted from environmental conditions.
Herbaceous	
71	Grassland/Herbaceous - areas dominated by gramanoid or herbaceous vegetation, generally greater than 80% of total vegetation. These areas are not subject to intensive management such as tilling, but can be utilized for grazing.
72	Sedge/Herbaceous - Alaska only areas dominated by sedges and forbs, generally greater than 80% of total vegetation. This type can occur with significant other grasses or other grass like plants, and includes sedge tundra, and sedge tussock tundra.
73	Lichens - Alaska only areas dominated by fruticose or foliose lichens generally greater than 80% of total vegetation.
74	Moss - Alaska only areas dominated by mosses, generally greater than 80% of total vegetation.
Planted/Cultivated	
81	Pasture/Hay – areas of grasses, legumes, or grass-legume mixtures planted for livestock grazing or the production of seed or hay crops, typically on a perennial cycle. Pasture/hay vegetation accounts for greater than 20% of total vegetation.
82	Cultivated Crops – areas used for the production of annual crops, such as corn, soybeans, vegetables, tobacco, and cotton, and also perennial woody crops such as orchards and vineyards. Crop vegetation accounts for greater than 20% of total vegetation. This class also includes all land being actively tilled.
Wetlands	
90	Woody Wetlands - areas where forest or shrubland vegetation accounts for greater than 20% of vegetative cover and the soil or substrate is periodically saturated with or covered with water.
95	Emergent Herbaceous Wetlands - Areas where perennial herbaceous vegetation accounts for greater than 80% of vegetative cover and the soil or substrate is periodically saturated with or covered with water.

Figure 3. NLCD Land-Use/Land-Cover Values and Classification Descriptions.
Source: USGS National Land Cover Data

Watershed Delineation

Hydrological units serve as physical boundaries that drain water from the land to river and stream systems. Each hydrologic unit is identified by a unique hydrologic unit code (HUC) consisting of a minimum two to a maximum of 12 digits. These HUCs are based on six levels of classification in the hydrologic unit system with smaller digit codes representing large geographic areas and larger digit codes representing smaller geographical areas. For example, two digit HUCs correlate with hydrologic regions, four digit HUCs with subregions, six digit HUCs with river basins, eight digit HUCs with subbasins, 10 digit HUCs with watersheds, and 12 digit HUCs with subwatersheds (USGS, 2012b). GIS hydrological unit layers will be downloaded from the USGS and imported into the National Land Cover Data (NLCD) classified imagery for 2001 and 2006. Using methods similar to Rothenberger et al. (2009), watersheds within each hydrological unit that contain water quality monitoring stations will be delineated using Arc GIS Hydro tools in addition to digital elevation models (DEMs) (30m) provided by the US Department of Agriculture's geospatial database. This will assist in understanding and illustrating surface water system flow patterns, the percent of a given LULC type within a watershed, and changes in land types from October 2000 to 2001 and October 2006 to October 2007.

Mapping Station Locations

The North Carolina Department of Environment and Natural Resources (NC DENR) Division of Water Resources (DWR) (formally the Division of Water Quality (DWQ)) and Cape Fear River Basin Assembly have developed Microsoft Excel documents that identify sampling locations by latitude and longitude. Latitude and longitude coordinates for each station will be imported from Microsoft Excel into Arc GIS 10 and converted to GIS point files. This information will be used to determine the spatial extent and exact location of water monitoring stations throughout the Cape Fear River Basin. Figures 4a, 4b, and 4c illustrate the locations of each monitoring station by river basin region.

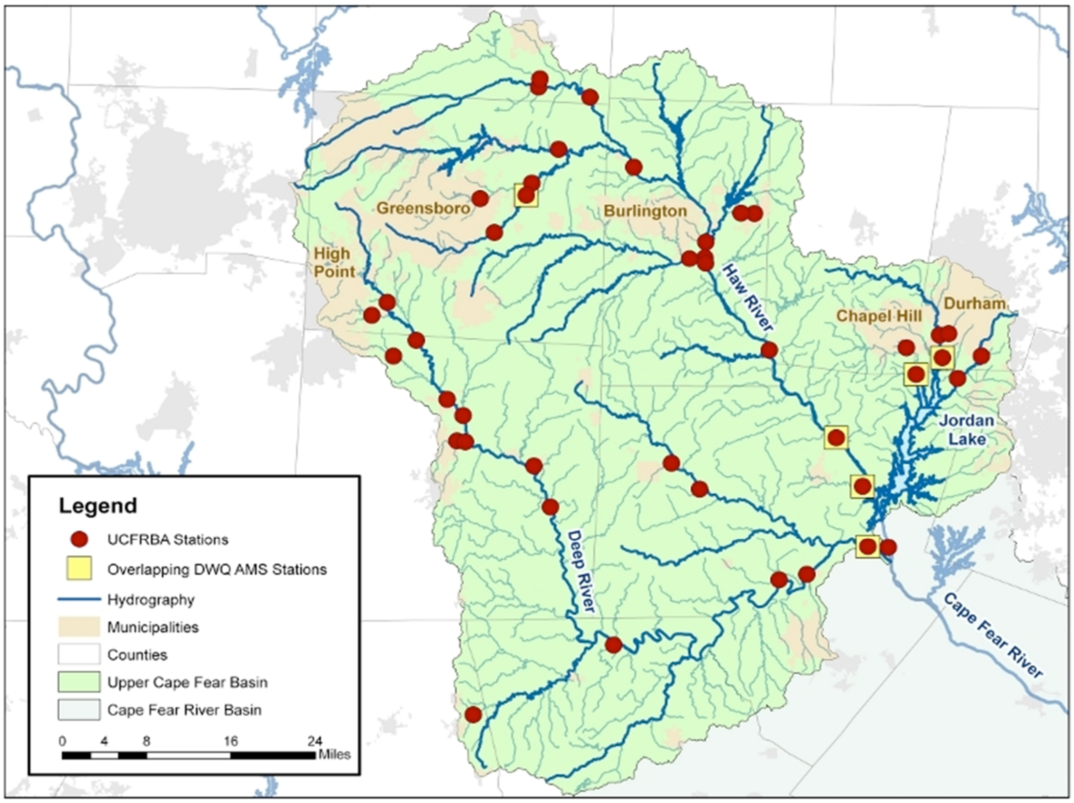

Figure 4a. The Upper Cape Fear River Basin Coalition's Water Quality Monitoring Stations. Source: NC DENR Division of Water Quality (2011)

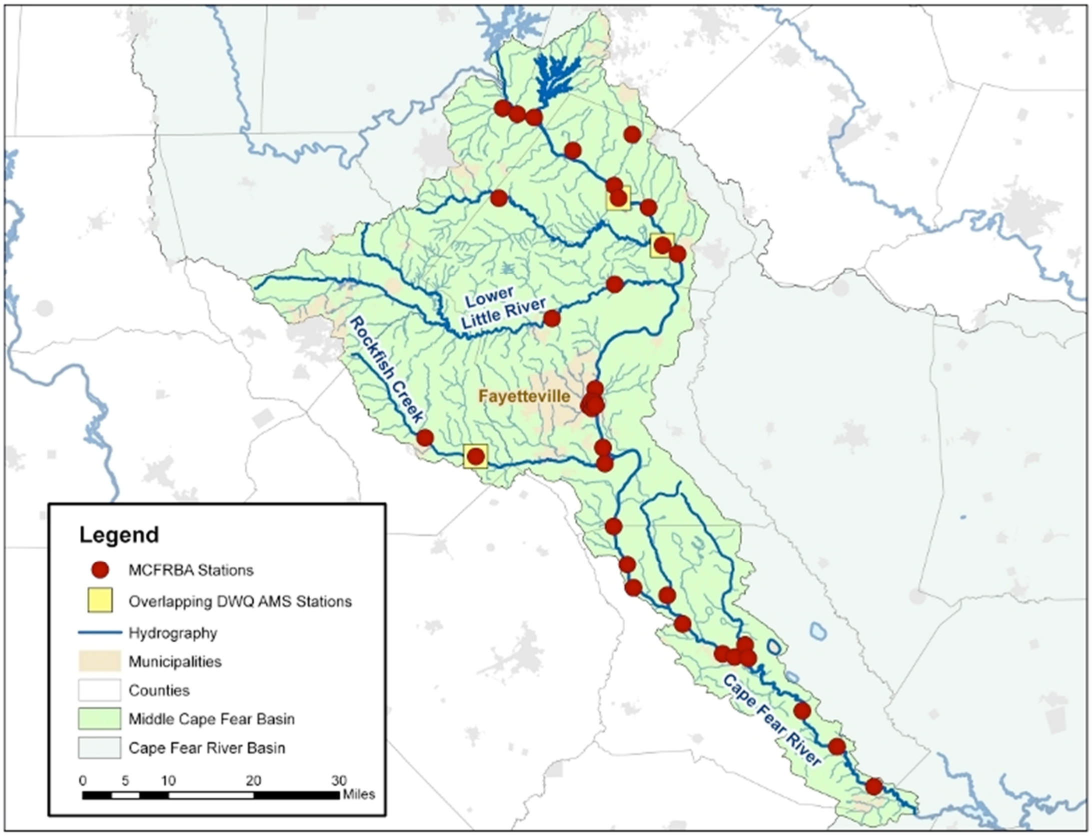

Figure 4b. The Middle Cape Fear River Basin Coalition's Water Quality Monitoring Stations. Source: NC DENR Division of Water Quality (2011)

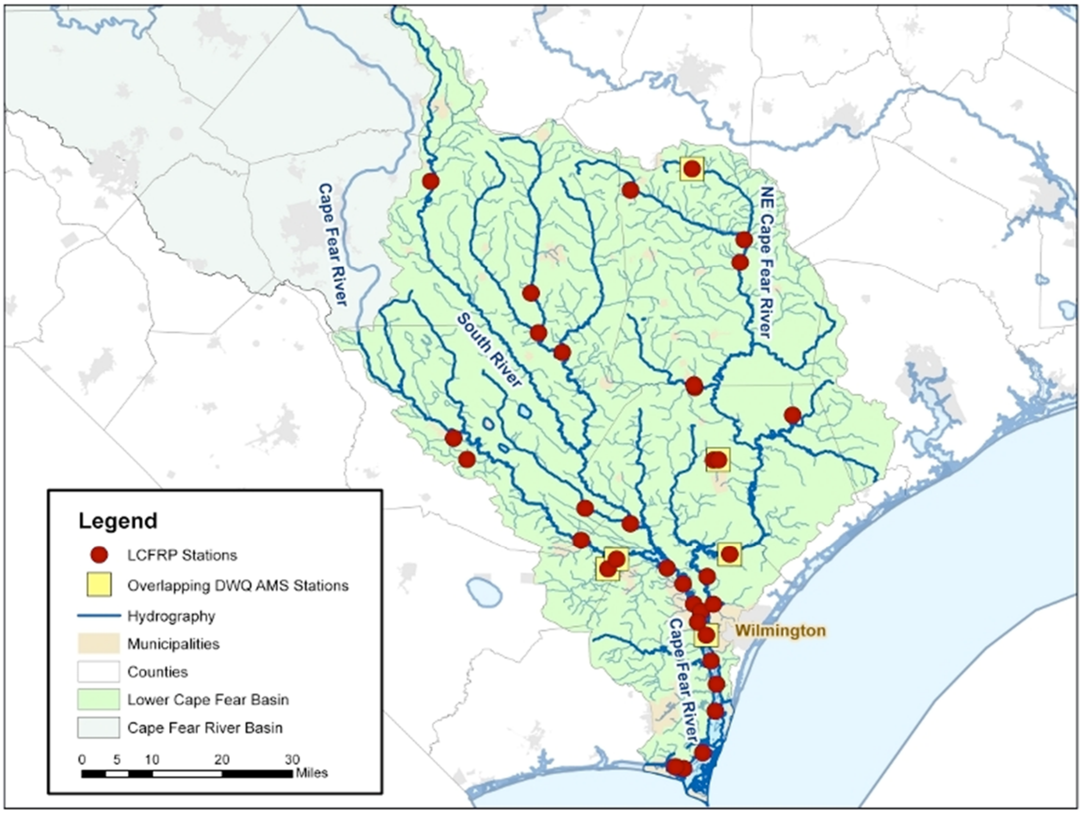

Figure 4c. The Lower Cape Fear River Basin Coalition's Water Quality Monitoring Stations. Source: NC DENR Division of Water Quality (2011)

Water Quality Analysis

Detailed water quality data for the entire Cape Fear River Basin dates back to 2000, with 144 water stations dispersed throughout the basin. Stations are monitored monthly for biological, chemical, and physical water quality parameters and annual reports are available for each station by parameter. Each water sample taken adheres to laboratory sampling techniques required by the NC Department of Environment and Natural Resources (DENR) Division of Water Resources (DWR). Water quality parameters of interest include fecal coliform bacteria, dissolved oxygen (DO), and nutrients including ammonium nitrogen (NH3-N), nitrate-nitrite (NO2-NO3), and phosphorus (P). Water quality data will be downloaded from Cape Fear River Basin Coalition's water quality data retrieval website.

The NC DENR Division of Water Resources (DWR) has established a water classification system for North Carolina's surface waters that determines the best use (e.g. drinking water, recreation, shellfish consumption) and if that use is being protected. For example, Class SA surface waters include tidal waters that are used for commercial shellfishing and have a maximum standard for fecal coliform of 43 col/100ml. If Class SA surface waters exceed 43 col/100ml that water body is designated as non-supporting of its intended use. The NC DENR water classification system was referenced to determine if surface water samples from a given station meets state water quality guidelines. Additionally, the NC DENR DWRs water quality exceedance reports will also be reviewed to identify impaired streams segments within the study area.

Variables of Interest

Based on prior studies and available data (Mallin et al., 2000; Brabec, 2009; Arnold & Gibbons, 1996; Schueler, 1994; Cookson & Schorn, 2009; Schoonover et al., 2005; Tu, 2011; Carle et al., 2005; Potter et al., 2004; Mallin & Cahoon, 2003; Rothenberger et al., 2009 and Burkholder et al., 2007), the following dependent and independent variables (Table 1) were analyzed in an effort to understand and spatially illustrate relationships between water quality and LULC types throughout the Cape Fear River Basin from 2001 to 2006. Data sources for the independent variables of interest can be obtained from federal, state, county, and municipal agencies. Using ArcGIS 10 software, this information is displayed on the classified LULC imagery. This is helpful in identifying significant changes related to these variables, as well as displaying the spatial distribution of the variables throughout the river basin and within each physiographic region.

Table 1. Dependent and Independent Variables of Interest

Dependent Variables	Independent Variables
Annual Average Dissolved Oxygen	Percent Land-Use/Land-Cover Type (km2)
Annual Average and Annual Geometric Mean fecal coliform	Number of Permitted Livestock Head by Permit
Annual Average Ammonium Nitrogen (NH3-N)	Total Precipitation
Annual Average Nitrate-Nitrite Nitrogen (NO2-NO3)	Type of Physiographic Region
Annual Average Phosphorus (P)	

Prior to developing regression models, calculations of each LULC type (i.e. percent km2) for the river basin and each physiographic region were completed. Additionally, the landscape drain to a specific water quality station were delineated to each water quality monitoring station included in this study to determine a given watershed's landscape characteristics. Livestock (i.e. cattle, swine, turkey) head counts for concentrated animal feeding operations (CAFOs) were obtained from DENR DWQ permits, which indicates the maximum number of livestock head allowed annually at a given operation site. Monthly total precipitation data were downloaded from the National Oceanic and Atmospheric Administrations (NOAAs) National Climatic Data Center and aggregated to represent the total annual precipitation. Weather stations were mapped in ArcGIS to determine which stations are closest to a given water quality station under investigation. This assists in estimating annual precipitation for each station since precipitation data are not collected at station sites. To understand differences in relationships between water quality parameters and different physiographic regions, dummy variables representing each of the three physiographic regions were developed and included in the analysis.

Statistical Data Analysis

Although Geographically Weighted Regression (GWR) models can be a very effective tool in assessing relationships between water quality and land types as noted by Tu et al. (2007), the data selection criteria in this study did not yield enough data points (i.e. n= <100) to develop successful GWR models. As a result, regression models and descriptive statistics were used to assess relationships between water quality and land types across the Cape Fear River Basin. In addition, this analysis considers if the location of point sources of pollution in relation to water monitoring stations may have contributed to poor water quality at both the river basin and watershed scales. The primary tool to complete the descriptive and statistical analysis for this study was SPSS 22.0.

Stream Classifications and Water Quality Guidelines

Water quality guidelines have been used at multiple geographical scales to determine if surface water quality is a threat to human and aquatic ecosystem health. These guidelines assist resource agencies with identifying and addressing impaired surface water systems as well as notifying the public of any potential health risk. The North Carolina Department of Environment and Natural Resources (NC DENR) Division of Water Resources (DWR) developed a surface water classification system in an effort to define best uses (e.g. fishing, drinking water supply, shellfishing, and swimming) of surface water systems as well as a set of water quality guidelines to protect those defined uses. These guidelines have evolved since their establishment in the 1950s in an effort to be consistent with the Federal Clean Water Act and its amendments. There are 12 primary surface water classifications, five of which define different protective measures for water supplies for human activities. All surface waters in North Carolina must, at a minimum, meet the Class C standard. Under this classification, waters must be protected for secondary recreational uses including fishing and fish consumption as well as protecting aquatic life. In addition, there are seven supplemental classifications that have been developed to provide special protection to sensitive or highly valued surface water systems. Supplemental classifications including the following: future water supply (FWS), nutrient sensitive waters (NSW), outstanding resource waters (OWR), swamp waters (Sw), high quality waters (HQW), trout waters (Tr), and unique wetlands (UWL). There may be multiple guidelines for a given stream segment. For example, in the CFRB there are streams classified as WS-IV B NSW meaning that this stream segment must meet all of the criteria for WS-IV, B, and NSW. In relation to water pollutants, NC DENR has established minimum and maximum guidelines for specific water quality pollutants (e.g. nutrients, fecal coliform bacteria) based on a given stream classification. For the purposes of this study if a standard has not been developed for a specific pollutant by the DWQ, the US EPA's water quality criteria was referenced. It should be noted that while these guidelines are defined for human use purposes, levels far below these guidelines will result in impaired waters for aquatic species. This highlights that although water policies may be established to protect human uses, they fail to address the true short term and long term ecological impacts water pollutants may have on local and regional ecosystems.

In the CFRB, in addition to the Class C standard, primary surface water classifications include Water Supply (WS I-V), Class SA (e.g. tidal salt waters used from commercial fishing), Class SC (e.g. all tidal salt water protected fishing and shellfish consumption), and Class B (e.g. primary recreation including swimming). Supplemental classifications in the basin include Sw, HQW, NSW, and OWR. When observing the spatial extent of stream classifications, one will note that WS-V are largely concentrated in the eastern portion of the UCFRB, Class C streams dominate the eastern portion of the UCFRB, and a majority of the MCFRB, and C Sw characterize the greater part of the LCFRB (Figure 5). Understanding these stream classifications and their locations assists in determining if water draining to a specific water quality station meets or exceeds the referenced water quality guidelines. In relation to the water quality parameters under investigation in this study, Table 2 highlights the NC DENR guidelines, EPA criteria, potential sources and impacts to both human health and aquatic species. In addition, Table 2 goes beyond each parameter's state and federal criteria to emphasize parameter levels and seasonal differences that may impact the health of aquatic ecosystem and species.

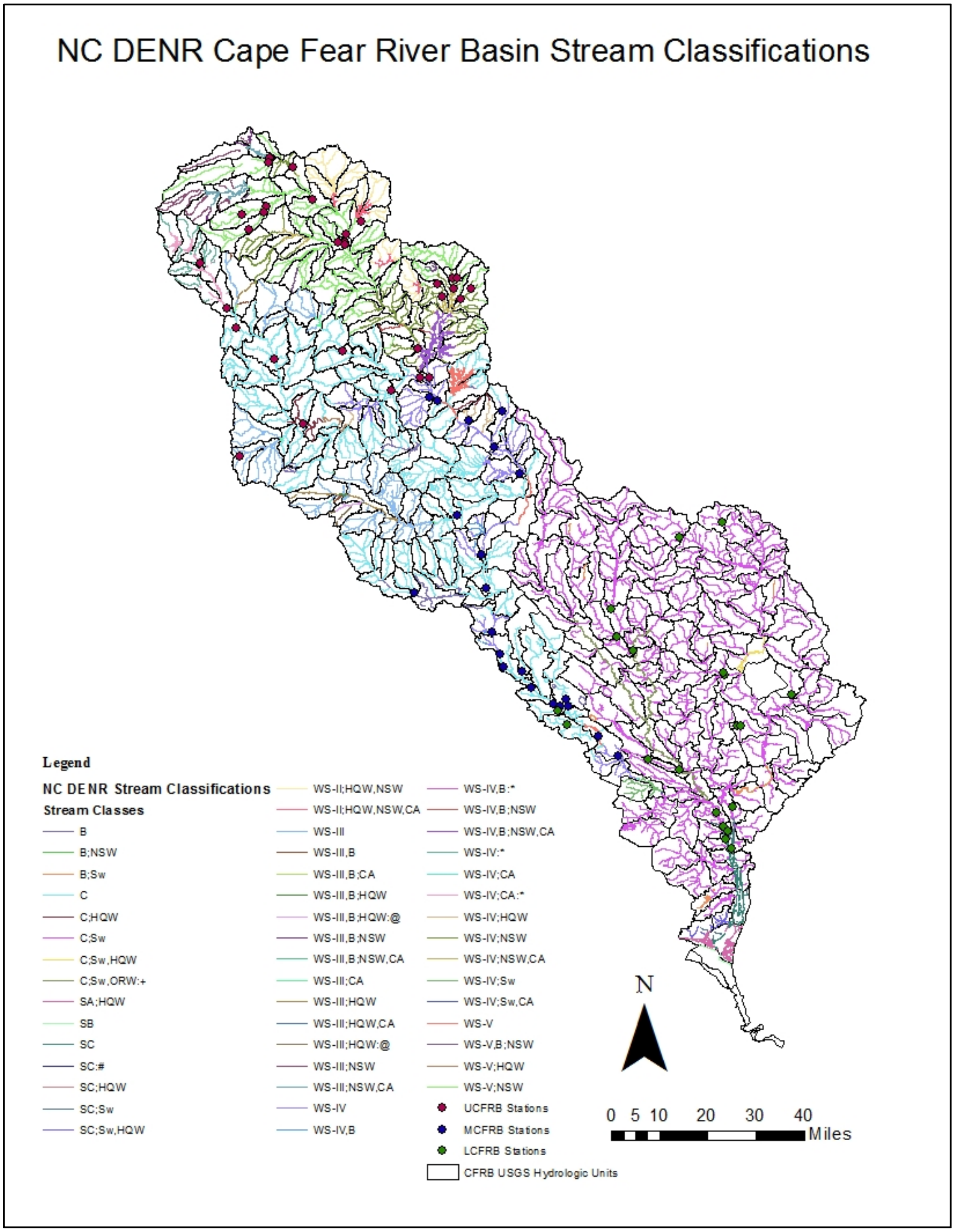

Figure 5. North Carolina Department of Environment and Natural Resources Stream Classifications: Cape Fear River Basin.

Table 2. Water Quality Parameter Guidelines and Recommendations for the Cape Fear River Basin Stream Classes.
Sources: US EPA, NC DENR, Cape Fear River Basin Monitoring Coalition

Water Quality Parameter	**Stream Classification**	**NC DENR Standard**	**US EPA Recommendations**	**Potential Sources and Seasonal Differences**	**Potential Problems**
Fecal coliform	All Stream except SA HQW	Maximum 400 col/100ml for all streams except SA HQW (43 col/100ml) or a geometric mean of 200 organisms/100mL in Class C Freshwaters and a geometric mean of 14 organisms/10mL in Class SA Saltwaters.	Currently working with state to develop new criteria based on more specific fecal characteristics.	Human sources may include wastewater treatment plant discharges, failing septic systems. Animal sources may include domestic pets, livestock, animal operations, and wildlife.	Human health risk including ear infections, dysentery, typhoid fever, and hepatitis A. Aquatic impacts include reduced DO resulting in fish kills and reduction in bacteria needed to balance aquatic systems.
Dissolved Oxygen (DO)	All streams except SA HQW and SC	Minimum 4 mg/L except SA HQW and SC (minimum 5 mg/L)	In most stream types, levels below 5.0 mg/L cause stressful conditions for aquatic ecosystems.	Increases with an increase in a streams contact with the atmosphere, high stream flow events, or produced by plants during photosynthetic processes. Decreases may result from an increase in nutrients, temperature, urban and agricultural runoff, land clearing, untreated sewage, and salinity. Higher DO may be common in the winter because the colder the water the more oxygen can be dissolved in the water.	At low levels of DO, impacts to aquatic ecosystems include the reduction in the number and the diversity of aquatic species.
Nutrients					
Nitrate-Nitrate Nitrogen (NO2-NO3)	Class WS only	<10 mg/L* *It is noted that this guideline is for human consumption and does not address ecosystem impairments.	<10 mg/*	Anthropocentric sources include wastewater treatment plants, runoff from fertilized lawns and cropland, failing septic tanks, runoff from animal manure storage areas, and industrial discharge. Natural sources may come from soil and rocks, the atmosphere, tissues of living and dead organisms. *Phosphorus is typically scarce in water under natural conditions. It is a vital nutrient for converting sunlight into usable energy and essential to cellular growth and reproduction. Seasonal differences may be related to precipitation events and/or crop rotation schedules, which may dictate when fertilizers are applied.	Excessive nutrients can accelerate eutrophication, causing dramatic increases in aquatic plant growth, which may change the types and amounts of aquatic species, can cause hypoxic conditions, and can become toxic to warm-blooded animals. Ammonia and nitrogen levels < 10 mg/L may cause stressful conditions for aquatic species.
Ammoniacal Nitrogen (NH3-N)	N/A	No NC DENR Standard	<10 mg/L		
*Phosphorus (P)	N/A	No NC DENR Standard	EPA limits point source permits to <1.0 mg/L		

Caveats

Several precautions were taken when proceeding with the methods and data applied in this research endeavor, particularly in relation to the land-cover/land-use (LULC) types, water quality data, and the types of stream classes. The Multi-Resolution Land Characteristics Consortium's (MRLC) classified LULC imagery for 2001 and 2006 do not reflect the true dates the images were taken for the Cape Fear River Basin (CFRB). Observing the metadata related to the 2001 and 2006 NLCD imagery, one will note several temporal differences across the physiographic regions. In 2001, path 15 row 36, representing the Middle and Lower basin, was taken on May 11, 2000. May is noted as being a "green up" or "leaf on" period in relation to vegetative cover. Given the extensive vegetative canopy cover in this portion of the basin, it may have been difficult for the image classifiers to observe impervious surfaces that may have been covered by vegetation growth during this period. For the UCFRB, path 16 row 35 was taken on October 7, 1999. This is the fall season when the remaining vegetation may have appeared brown in the imagery and the loss of vegetative cover may have enabled classifiers to classify more impervious surface in this portion of the basin when compared to the Middle and Lower CFRB. For 2006, the imagery for the UCFRB, was taken on October 15, 2005 and for the Lower and Middle portions of the basin on April 21, 2007 representing similar classification problems as the 2001 imagery. It is imperative in this analysis to consider the potential errors made by the image classifiers, such as not classifying all of the developed landscape within with Lower and Middle basins during the May/April "leaf on" period. For the purposes of this study, the imagery dates will often be referred to 2001 and 2006 to be consistent with other studies that have applied this datum.

Analyzing water quality data provided by the CFRB Monitoring Coalitions' Water Quality Data website (i.e. a partnership between the Cape Fear River Basin Assembly and the NC

DENR Division of Water Resources (DWR)) requires taking several precautions in an effort to accurately portray water quality characteristics and changes throughout the study area. For example, there are 144 monitoring stations located throughout the CFRB, many of the stations in the UCFRB and MCFRB do not provide complete monthly data and or continuous data for the period under investigation in this study. As a result, several parameters and stations will be excluded from the analysis because they were not consistently sampled during the period of this study. When considering the samples themselves, typically, a sampler takes a sample once a month around the same time period (e.g. during the first two weeks of the month), however, this sampling period may vary by physiographic region. In addition, flow data is a key factor in determining concentrations of water quality parameters as well as the impact of precipitation events on stream water flows. The NC DENR DWQ staff indicated that although water flow data is not taken for each site, samples are not collected unless flow is present at the time of sampling (NC DENR Personal Communication, July 2013). One important analysis strategy that needs to be noted is that monthly water quality data for each station will be averaged to better align with the satellite imagery. It is understood that taking the average of each parameter may mask seasonal differences as well as spikes that may occur because of specific events (i.e. wastewater spills). Although annual averages will be used to develop regression models, the descriptive statistics will highlight seasonal differences and spikes that may occur for each station under observation.

As a result of the gaps in available water quality data and temporal limitations related to the NLCD 2001/2006 imagery, water quality stations were selected if they had complete monthly data from October 2000 to October 2001 (i.e. 2001) and from October 2006 to October 2007 (i.e. 2006)for the following parameters: dissolved oxygen (DO), fecal coliform, phosphorus (P), ammonium nitrogen (NH3-N) and nitrate-nitrite nitrogen (NO2-NO3). In addition, 18 stations were excluded from this analysis because the watershed area that drains to them could not be accurately delineated using ArcHydro tools. This may be a result of the resolution used in creating the digital elevation model (DEMs) (i.e. 30m) and or flaws in the software delineating each watershed. In addition, many of the watersheds draining watersheds in the LCFRB with high numbers of CAFOs are very small and 30x30m resolution imagery, such as the type used in this assessment, cannot define these small watershed areas. Although CAFOs that are permitted by the NC DENR are identified there are several poultry CAFOs whose exact headcounts and practices are unknown to the public. Figure 6 illustrates that while CAFO facilities may not cover a large spatial extent on a single parcel of land, the high concentrations of these across the landscape illustrates that their presence and activities (e.g spraying raw fecal on the landscape) lead to impaired water quality both locally and downstream. The water quality temporal criteria and watershed delineation flaws resulted in 72 water quality stations being included in this analysis. It should be further noted that given these conditions many of the stations in the LCFRB that are located in watersheds that contain a high number of CAFOs have been excluded from this study. Several studies (Mallin & Cahoon, 2003; Mallin et al., 2006; Mallin et al., 2004) have observed impaired water quality positively correlated with high nutrient and fecal concentrations in several of these watersheds further highlighting how human activities may impact water quality within the CFRB.

The location of stations across the CFRB lends itself to additional considerations regarding the data observed in this study. The CFRB Coalition's monitoring program was originally established to monitor water quality up and down stream of point source discharge locations (e.g. wastewater treatment facilities and industrial factories).

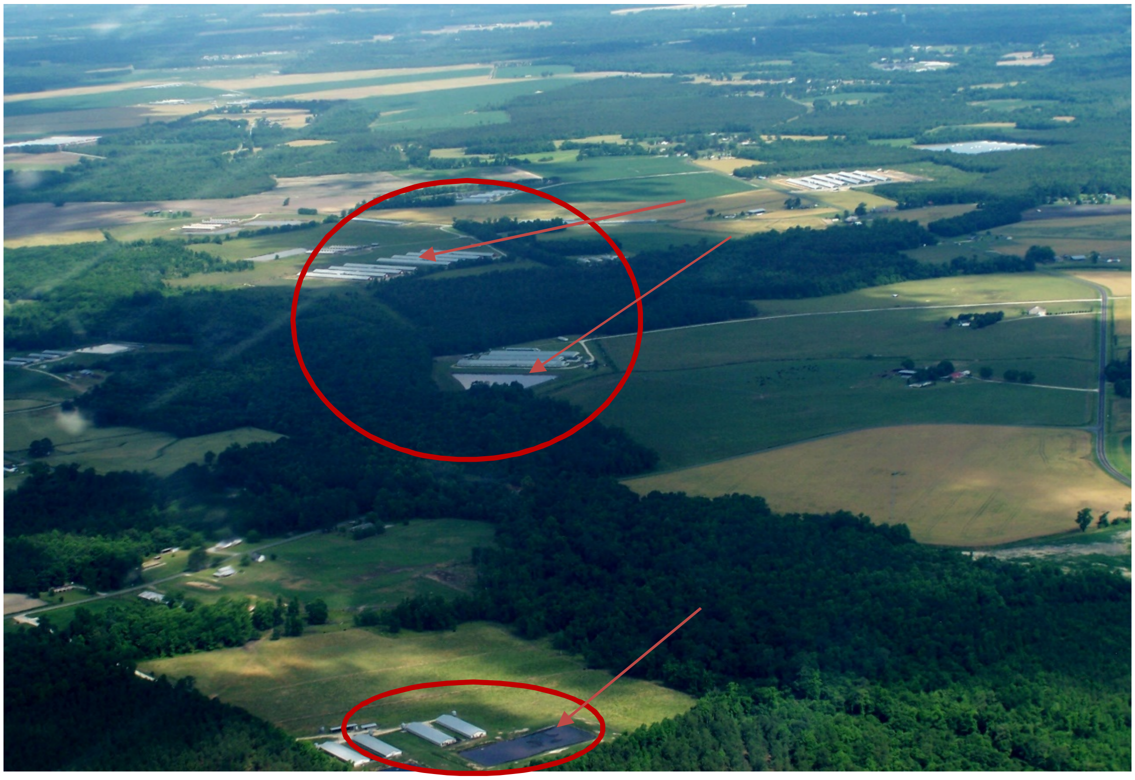

Figure 6. CAFO Facilities and Waste Lagoons Located in Duplin County, NC in 2013.
Source: Mallin, 2013

Since this time, the program has expanded to include additional monitoring locations in an effort to consider non-point sources of surface water pollution. Depending on a station's location it may be monitoring drainage from a single or multiple watersheds (i.e. nested) upstream from its location. Some of the stations included in this program are located along the main stem (i.e. Cape Fear River) of the river system, while other stations are located along stream tributaries (e.g. first and second order streams) that flow into the main stem. For example, in Figure 7 UCFRB station 05 is draining a single watershed. In contrast, UCFRB station 06 is nested, which includes the watershed draining to UCFRB station 05. When this occurs we state that watershed draining to UCFRB station 05 is nested within the landscape draining to UCFRB station 06. Stations draining multiple watersheds represent water quality parameter concentrations that another station may be capturing (e.g. UCFRB station 05) plus water quality parameter concentrations related to additional watersheds, such as the case with UCFRB station 06. Stations draining single verses nested watersheds will be noted throughout the study. Following the methods outlined in this chapter may illustrate and describe relationships between water quality parameters and LULC across the basin as well as changes from 2001 to 2006.

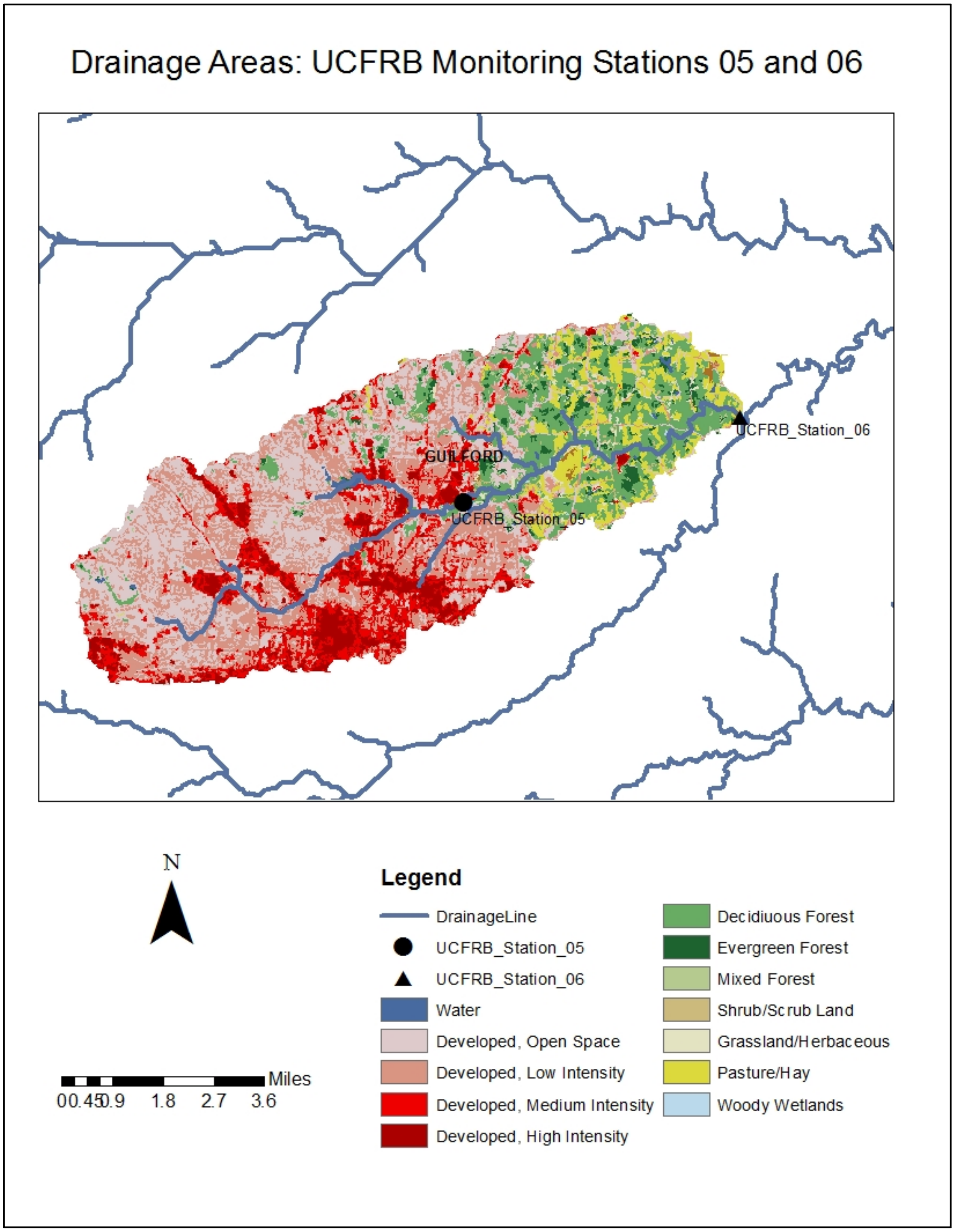

Figure 7. Watershed Drainage Patterns for Upper CFRB Stations 05 and 06.

CHAPTER IV

RESULTS AND DISCUSSION

Surface water resources are essential to sustain human and wildlife populations. As the population of the Cape Fear River Basin (CFRB) continues to grow, it will become increasingly important for resource agencies to protect surface water quality and to develop coherent strategies related to how this resource will be allocated throughout the basin. Over the past three decades, the CFRB has experienced significant increases in human related activities that have frequently impaired the quality of surface water resources. For example, increases in fecal coliform and nutrients (i.e. nitrate-nitrite (NO2-NO3), ammonium nitrogen (NH3-N), phosphorus (P)) and low dissolved oxygen (DO) have all been associated with the impairment of surface water quality in the CFRB. Increases in fecal coliform and nutrients have resulted from significant wastewater sewer spills, a shift in agricultural practices (i.e. from pasture to concentrated animal feeding operations (CAFOs), and increases in impervious surfaces throughout the basin (NC DENR, 2000, 2005; Mallin, 2012).

Although this study considers changes in water quality and LULC types from October 2000 to 2001 (i.e. 2001) and October 2006 to October 2007 (i.e. 2006), large-scale industrial spills including wastewater system spills and CAFO activities continue to take place throughout the river basin. Recently, a wastewater treatment plant (WWTP) spill occurred on May 2013, where 442,000 gallons of untreated sewage was discharged into Hewletts Creek, a tidal creek system in the LCFRB that drains into the Intracoastal Waterway and eventually the Atlantic

Ocean (Wilmington Star News, 2013). Additionally, activities associated with CAFOs serve as a major source of both fecal coliform and nutrients that can enter surface waters within the basin. Mallin and Cahoon (2003) note several case in the Coastal Plains of the CFRB where CAFO activities, including spraying fecal material onto fields adjacent to river and stream systems, have resulted in large increases in fecal and nutrients entering ground and surface water systems. Increases in fecal and nutrients have been linked to low DO levels in these systems resulting in both a reduction in surface water quality and the abundance and quality of aquatic ecosystems. In addition to numerous documented sources that contribute to impaired water quality in the CFRB, the basin is also the most industrialized basin in North Carolina and contains multiple power plants. Although national attention has been given to the large scale coal ash spill in the Dan River Basin northwest of the CFRB, recently North Carolina regulators reported that Duke Energy illegally pumped 61 million gallons of contaminated water from a coal ash pit into the Cape Fear River (Cape Fear River Watch, 2014). Although the long-term ecological impacts of this activity are unknown at this time, this is one of many events that magnify the need to address how human activities and decisions regarding land types at both the local and regional scales impact surface water quality throughout the basin. Given the geographical extent of fecal coliform bacteria, DO, and nutrient issues and their relationships to varying land types and activities in the CFRB, this study will concentrate on examining relationships between these water quality parameters and LULC types throughout the basin. Specifically, this study will address the spatial distribution of these parameters at the river basin scale and will identify key watersheds that have exceeded NC DENR water quality guidelines or EPA recommendations for parameters with no state standard/guideline within each of the physiographic regions (Table 2).

The Geography of Water Quality and Land-Use/Land-Cover Types in the Cape Fear River Basin

Water Quality and Land-Use/Land-Cover Across the Cape Fear River Basin

At the river basin scale, fecal coliform is the most variable water quality parameter with the highest standard deviation as well as the parameter that most frequently exceeded the NC DENR guideline for fecal (< 400 col/100ml) from October 2000 to October 2001(i.e. 2001) and from October 2006 to October 2007 (i.e. 2006) (Tables 3 and 4).

Table 3. 2001 Descriptive Statistics for the Annual Averages of Water Quality Parameters for Stations Located in the Cape Fear River Basin. n = 72

Water Quality Parameters	Minimum	Maximum	Mean	Standard Deviation	Number of Stations with Annual Averages Exceeding State/EPA Guidelines
Fecal coliform (col/100ml)	18	3,618	415	707	19
DO (mg/L)	4.17	11.02	8.08	1.13	0
NO2-NO3 (mg/L)	0.05	9.22	1.27	1.87	0
NH3-N (mg/L)	0.03	0.82	0.12	0.13	0
P (mg/L)	0.03	2.14	0.27	0.30	1

Further inspection of the annual averages of water quality parameters across the river basin revealed that only one station (UCFRB 06) exceeded NC DENR guidelines for nitrate-nitrite nitrogen (NO2-NO3) in 2006 (12.54 mg/L) and none of the station's annual averages exceeded NC DENR guideline for dissolved oxygen (DO) when applying the stream classification system. When applying the EPA recommendation for phosphorus (P) (<1.0 mg/L) and ammonium nitrogen (NH3-N) (<10 mg/L), UCFRB station 39 exceeded the recommendation for P in both 2001 and 2006 (2.14 mg/L, 1.07 mg/L) and LCFRB station BC117 (1.72 mg/L) exceeded this recommendation in 2006. In relation to NH3-N, none of the station's annual averages exceeded the EPA recommendations.

Table 4. 2006 Descriptive Statistics for the Annual Averages of Water Quality Parameters for Stations Located in the Cape Fear River Basin. n = 72

Water Quality Parameters	**Minimum**	**Maximum**	**Mean**	**Standard Deviation**	**Number of Stations with Annual Averages Exceeding State/EPA Guidelines**
Fecal coliform (col/100ml)	24	1,472	318	327	23
DO (mg/L)	5.03	10.65	8.06	1.15	0
NO2-NO3 (mg/L)	0.06	12.54	1.32	2.29	2
NH3-N (mg/L)	0.03	0.32	0.07	0.044	0
P (mg/L)	0.03	1.72	0.19	0.25	2

Further inspection of the annual averages of water quality parameters across the river basin revealed that only one station (UCFRB 06) exceeded NC DENR guidelines for nitrate-nitrite nitrogen (NO2-NO3) in 2006 (12.54 mg/L) and none of the station's annual averages exceeded NC DENR guidelines for dissolved oxygen (DO) when applying the stream classification system. When applying the EPA recommendation for phosphorus (P) (<1.0 mg/L) and ammonium nitrogen (NH3-N) (<10 mg/L), UCFRB station 39 exceeded the recommendation for P in both 2001 and 2006 (2.14 mg/L, 1.07 mg/L) and LCFRB station BC117 (1.72 mg/L) exceeded this recommendation in 2006. In relation to NH3-N, none of the station's annual averages exceeded the EPA recommendations.

As previously noted, the state and federal guidelines for the water quality parameters under investigation may represent guidelines associated with human uses (e.g. drinking water, recreation) and may not reflect the extent to which inputs to stream and river systems impact ecological processes. Another consideration when analyzing water quality parameters is the extent to which seasonal variations in hydrology, climatic conditions, and watershed activities influence seasonal variability among a given parameter. For example, natural seasonal variations in DO in streams and rivers are well documented, however, several studies have linked human disturbances to the natural landscape with fluctuations in DO levels. Typically, DO is higher in winter months because colder water can absorb more oxygen, so applying an annual average to each station may mask seasonal differences in DO. Another common impairment of surface water systems are algal blooms associated with increases in fecal and nutrients. The presence of algal blooms may result in decreases in DO and are more prevalent in warmer temperatures and during periods of low stream flow. Naturally, DO may vary in river and stream systems due to climatic, topographical, biological, and geological conditions. For example, wetlands have been known to exhibit naturally low levels of DO because of the lack of topographical changes in the stream bed that increase the interface between the atmosphere and water column, thus increasing DO in surface water systems. In addition, blackwater streams that characterize a majority of the Coastal Plains of North Carolina are naturally low in DO. This has been linked to the slow movement of water and extended contact with underlying sediments in the instream swamps that characterize blackwater systems. Observing DO levels from June to September for all 72 stations, one will note that 9 stations exceeded the state standard for DO in 2001 and 17 stations exceeded the state standard from October 2006 to October 2007 (i.e. 2006) with a majority of these stations being located in the LCFRB.

It should also be noted that the geometric mean is often used when reporting fecal coliform. When applying the NC DENR geometric mean standard for fecal (200 organisms/100mL) five stations exceeded this standard in 2001 and in 2006. In 2001, all of these stations were located in the UCFRB, while in 2006 they were spatially distributed throughout the basin. Since fecal coliform is so variable at the river basin and physiographic region scales and it was the parameter with both monthly and annual averages that most frequently exceeded the state guideline, it will be the focal point of discussion. Specific watersheds located within each of the physiographic regions with stations whose annual averages exceeded NC DENR fecal guidelines will be discussed in more detail in the forthcoming sections. This analytical approach will assist in identifying and addressing the spatial characteristics of this parameter and highlight LULC types and changes in watersheds with stations that exceeded the state guideline.

Fecal Coliform

In an effort to understand why fecal coliform is highly variable from October 2000 to 2001 (i.e. 2001) and from October 2006 to October 2007 (i.e. 2006) across the river basin, descriptive statistics were evaluated to identify station annual averages that exceeded the NC DENR guideline (400 col/100ml) as well as stations that exhibited significant changes in fecal from 2001 to 2006. In 2001, water quality annual averages by station for fecal coliform varied from a low of 18 col/100ml (MCFRB 23) to a high of 3,618 col/100ml (UCFRB 39) with a mean of 415 col/100ml (Table 3). When applying the geometric mean, fecal counts ranged from a low of 9 col/100ml (MCFRB 23) to a high of 1,774 col/100ml (UCFRB 39) with an overall geometric mean of 123 col/100ml. In 2006, water quality station annual averages for fecal concentrations ranged from a low of 24 col/100ml (UCFRB 29) to a high of 1,472 col/100ml (MCFRB 24) with an annual mean of 318 col/100ml (Table 4). When applying the geometric mean to station annual averaged in 2006 the lowest was 13 col/100ml (MCFRB 24) and the highest fecal count across the basin was 688 col/100ml (UCFRB 39) with a mean of 98 col/100ml. Both the annual average and geometric mean for UCFRB stations 05, 06, 07, 08, and 39 exceeded state guidelines in 2001. In 2006, UCFRB stations 24, 25, 39, MCFRB station 12, and LCFRB station BC117 exceeded state guidelines for fecal and stations UCFRB 25, 39; MCFRB 12; and LCFRB BC117 exceeded the state guideline when applying the geometric mean. Although the highest annual average for fecal decreased by 2,145 col/100ml from 2001 to 2006 across the basin, a larger percentage of water quality stations throughout the basin (32%) exceeded the state guideline in 2006 when compared to 2001 (26%). Statistically, these changes resulted in a lower standard deviation and variance in 2006 indicating that the spread of the values were closer to the mean in 2006 when compared to 2001.

Figures 8 and 9 illustrate the spatial extent of station annual averages that exceeded the state guideline for fecal coliform for October 2000 to October 2001 and October 2006 to October 2007. The spatial distribution of these stations illustrate that from October 2000 to October 2001 these stations were located in the UCFRB and MCFRB (Figure 8). In contrast, stations exceeding this guideline from October 2006 to October 2007 were located across all three of the physiographic regions (Figure 9). When considering stations with annual averages that exceeded fecal guideline across the river basin, the UCFRB represented the physiographic region with the largest percentage of stations that exceeded the state guideline for fecal in both 2001 (84%) and 2006 (56%). A majority of these stations were located in watersheds characterized by either developed areas or watersheds that were largely inclusive of both forest and agricultural areas. These findings illustrate that various land types and patterns may contribute to increases in fecal concentrations across different geographical scales. Seven water quality station's annual averages exceeded the guideline for fecal coliform during ***both*** of these time periods. Six of these stations (UCFRB stations 24, 27, 37, 38, 39, 42) are located in the UCFRB in watersheds that largely encompassed forest and/or hay/pasture land types. The seventh station, located in the MCFRB (MCFRB 12), drains a watershed that was largely characterized by evergreen forest and woody wetlands. Excessive fecal has been linked to different land types including agricultural, urban, and forested landscapes. A majority of the literature has observed excessive fecal concentrations in and around urban and agricultural areas, however, fecal has also been associated with forested landscapes. Although not as common, the association between increases in fecal counts and forest land types has previously been linked to logging activities, the presence of wildlife, and outdoor recreation activities including horseback riding and hunting trails (Line et al., 2008; Ensign & Mallin, 2001). In relation to watersheds with woody wetlands, wetland ecosystems have been associated with improved surface water quality; however, when these ecosystems experience excessive concentrations of pollution they may become ineffective in removing pollutants from surface waters (Verhoeven et al., 2006; Brinson, 1993; Fink et al., 2004; Mitsch et al., 2001).

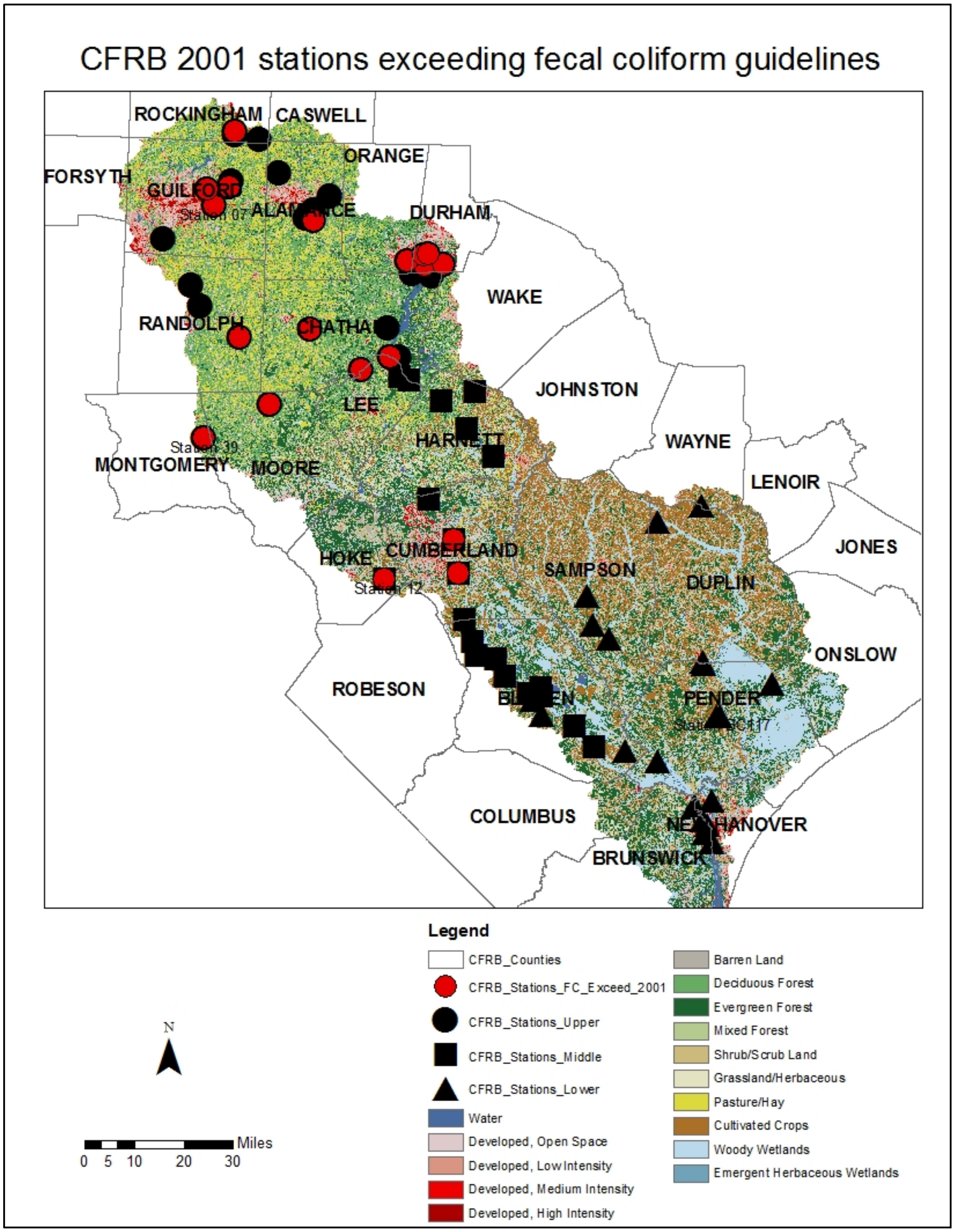

Figure 8. Cape Fear River Basin Stations Exceeding Fecal Coliform Guidelines from October 2000 to October 2001.

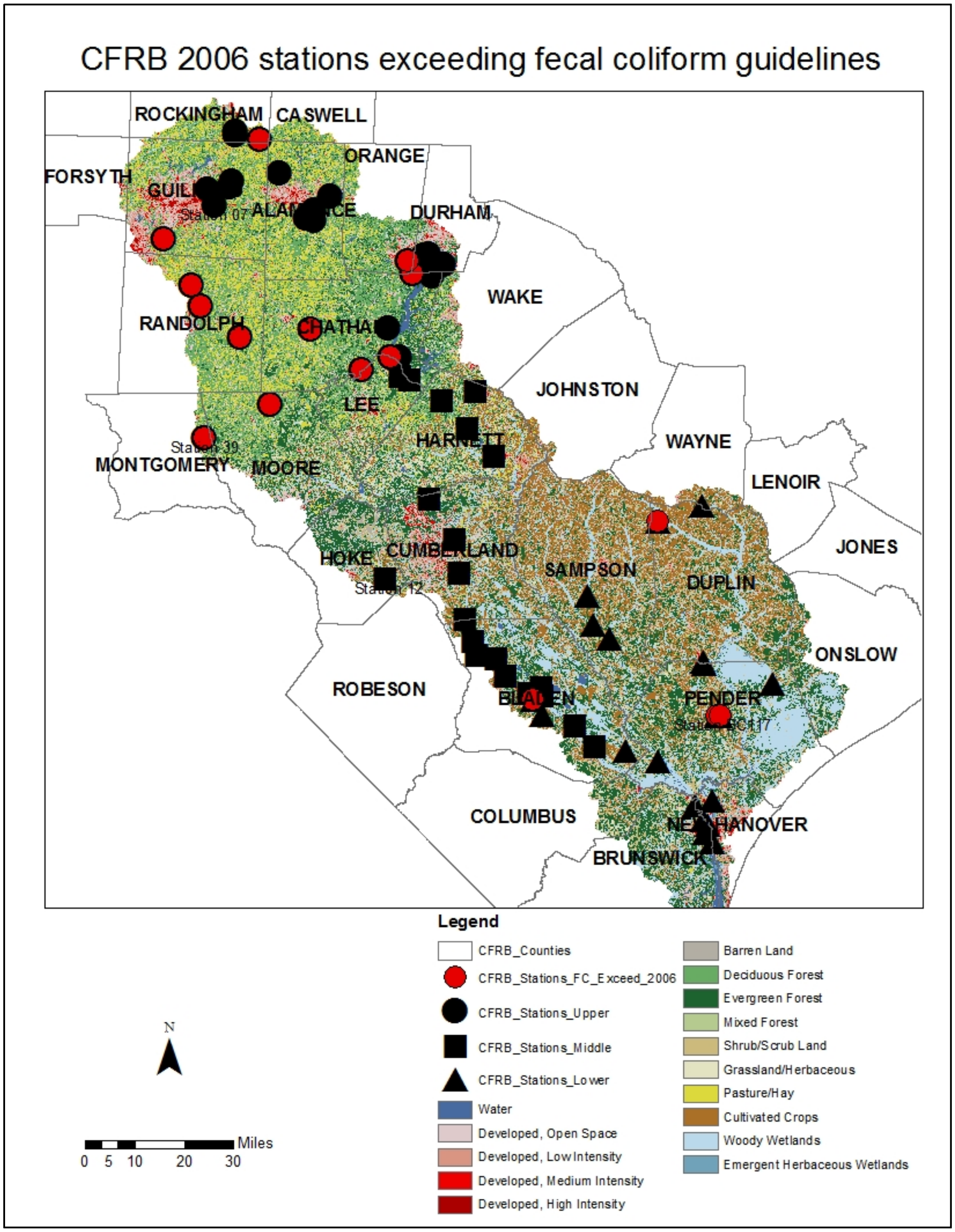

Figure 9. Cape Fear River Basin Stations Exceeding Fecal Coliform Guidelines from October 2006 to October 2007.

Changes in Land-Use/Land-Cover Types

When comparing LULC changes to water quality parameter annual averages at the river basin scale, one will note that while water quality parameters were variable, land types were primarily stable as indicated by little to no change from October 2000 to October 2001 (i.e. 2001) to October 2006 to October 2007 (i.e. 2006). Although the changes were minute, both agricultural and developed areas slightly increased with development representing a larger portion of this increase (0.14% km2). In contrast, both forest and wetland areas decreased; with forestland representing the largest decrease (0.33% km2) across the river basin (Figure 10).

Within each of the physiographic regions, agricultural land types represented the largest increase when compared to development, while forested land represented the largest decrease. Specifically, the LCFRB represented the physiographic region that experienced the largest increase (1.39% km2) in agricultural land, while the MCFRB represented the region with the largest increase in development (0.66% km2). The increase in agricultural areas in the LCFRB may be attributed to new land being put into agricultural production and/or land that had been previously left fallow from October 2000 to October 2001 being put into production from October 2006 to October 2007. In the MCFRB, increases in development may be contributed to the increase in military personnel at Fort Bragg Military Base. This increase was driven in part by the United State Defense Departments' decision to close and consolidate several military bases throughout the United States from 1988 to 2005, which subsequently led to increases in populations in and the surrounding bases that remained active, including Fort Bragg.

Spatially, development was concentrated when compared to other LULC types found throughout the basin. Developed areas are primarily located in Guilford, Alamance, Orange, and Durham counties in the UCFRB, Cumberland and Hoke counties in the MCFRB, and New

Hanover County in the LCFRB (Figures 10 and 11). Increases in development were largely represented by exurban development and low intensity development.

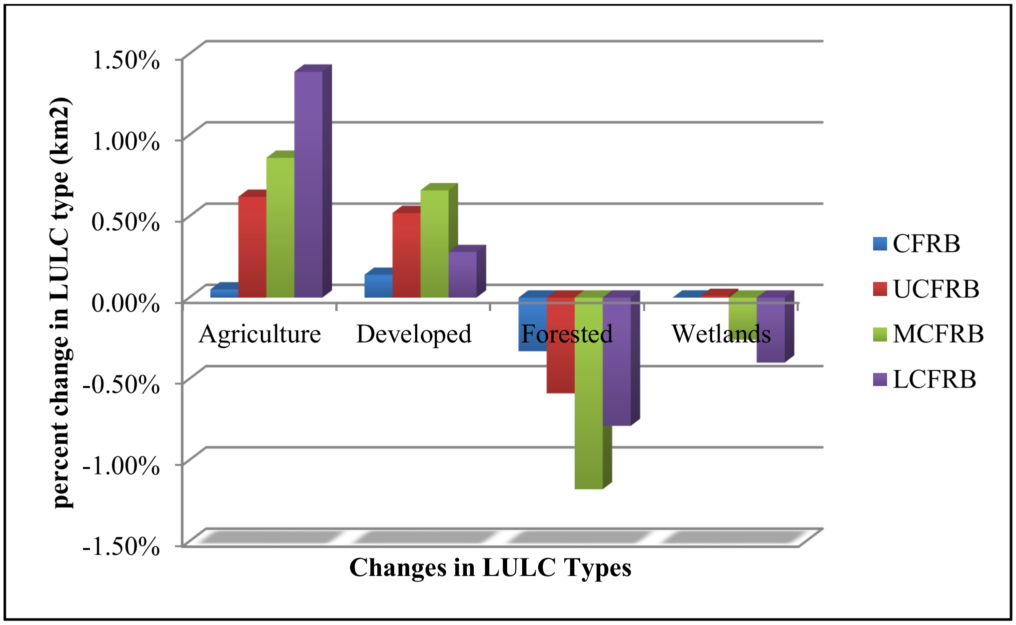

Figure 10. Percent Changes in LULC Types at Various Geographical Scales: Cape Fear River Basin, October 2000 to October 2001 and October 2006 to October 2007.

These land types are characterized by dispersed patterns and low percentages of impervious surfaces. It is important to note that a majority of these urban areas are located in the UCFRB near or are inclusive of the headwaters of the Deep and Haw Rivers that eventually join downstream to form the Cape Fear River. In relation to agricultural areas, hay/pasture was primarily located in the UCFRB, while cultivated crops represented a majority of the agricultural land in the MCFRB and LCFRB regions. It should be noted that although LULC types can be key in understanding relationships between the landscape and water quality, the focus may need to extend beyond these broad categories to be inclusive of the different types of activities taking place on various landscapes in an effort to more accurately represent these relationships.

As previously mentioned, wastewater treatment plant (WWTP) spills, septic system failures, and Concentrated Animal Feeding Operations (CAFOs) activities have been linked to increases in nutrients and pathogens, including fecal coliform bacteria, in surface water systems across the nation including the CFRB (Mallin et al., 2000; Smith et al., 2001; Ahearn et al., 2005; Burkholder et al., 2007; Rothenberger et al., 2009; Mallin & Cahoon, 2003). WWTPs are found throughout the river basin and are typically associated with development. When considering the impacts of WWTPs on surface water quality, one must take into consideration that although permitted discharge activities occur at the facility, WWTPs are connected to spatially dispersed piping systems that may extend dozens of miles from the WWTPs. Overtime, these pipe systems may experience spills and leaks that can contribute to poor surface water quality. In addition to WWTPs, a significant number if CAFOs are located throughout the basin, with the largest concentration occurring in the northeastern portion of the LCFRB (Figure 2).

Analysis of NC DENR animal feeding operation permits indicates that there are approximately 8 million permitted heads of livestock (i.e. cattle, swine, poultry) known to be located in 58 percent of the watersheds under investigation in this study, although more could have been present. When considering relationships between LULC types and water quality trends related to fecal bacteria, it is not likely that land types alone resulted in the drastic variability in fecal counts since there was little change in land types from October 2000 to 2001 and October 2006 to October 2007. It is more likely, however, that the activities taking place (e.g. spraying manure waste onto fields) or the presence of human made landscape features, such as the existence of WWTPs, CAFOs, and septic systems may have resulted in significant variability in fecal concentrations across the basin.

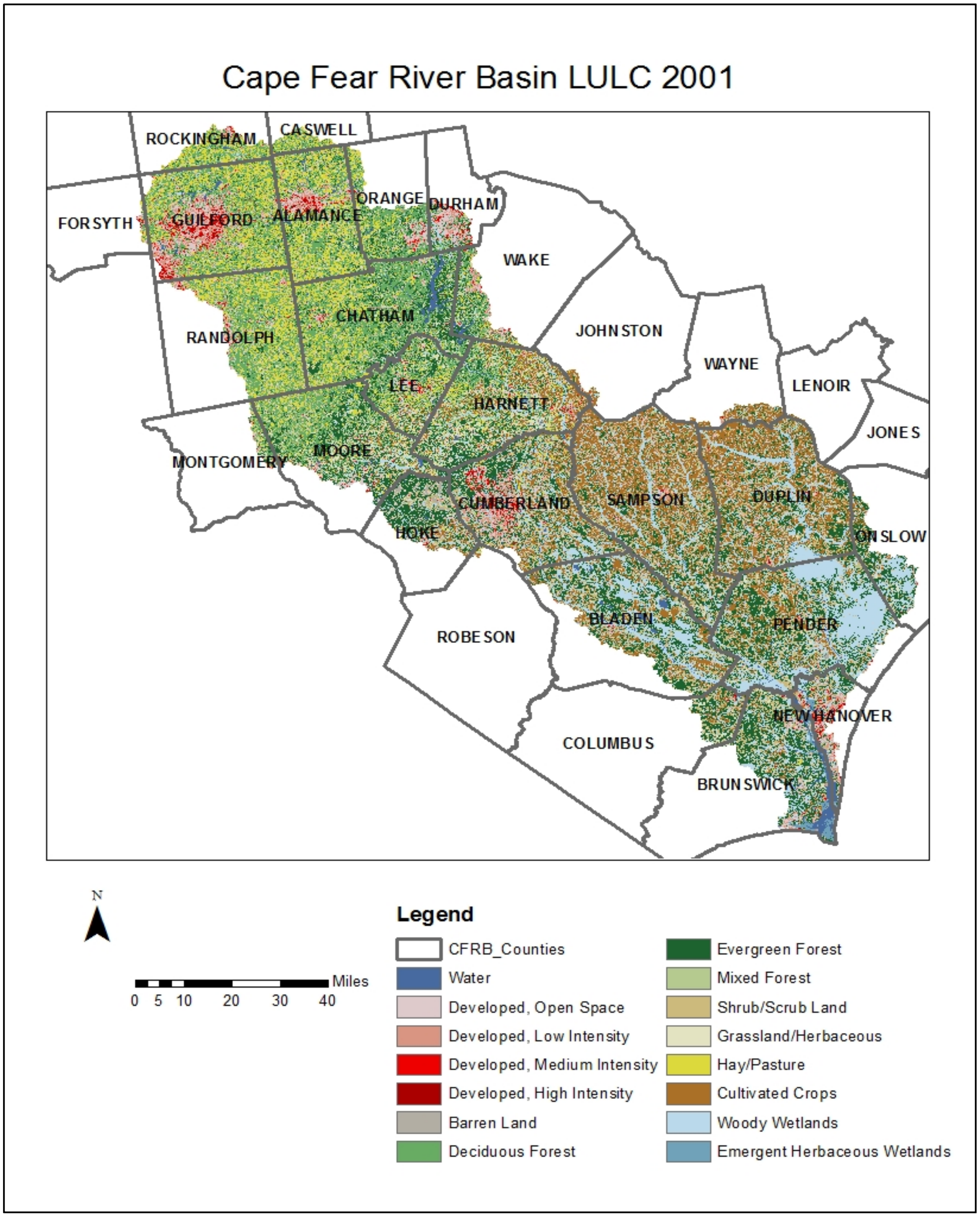

Figure 11. Land-Use/Land-Cover Types Across the Cape Fear River Basin, 2001.

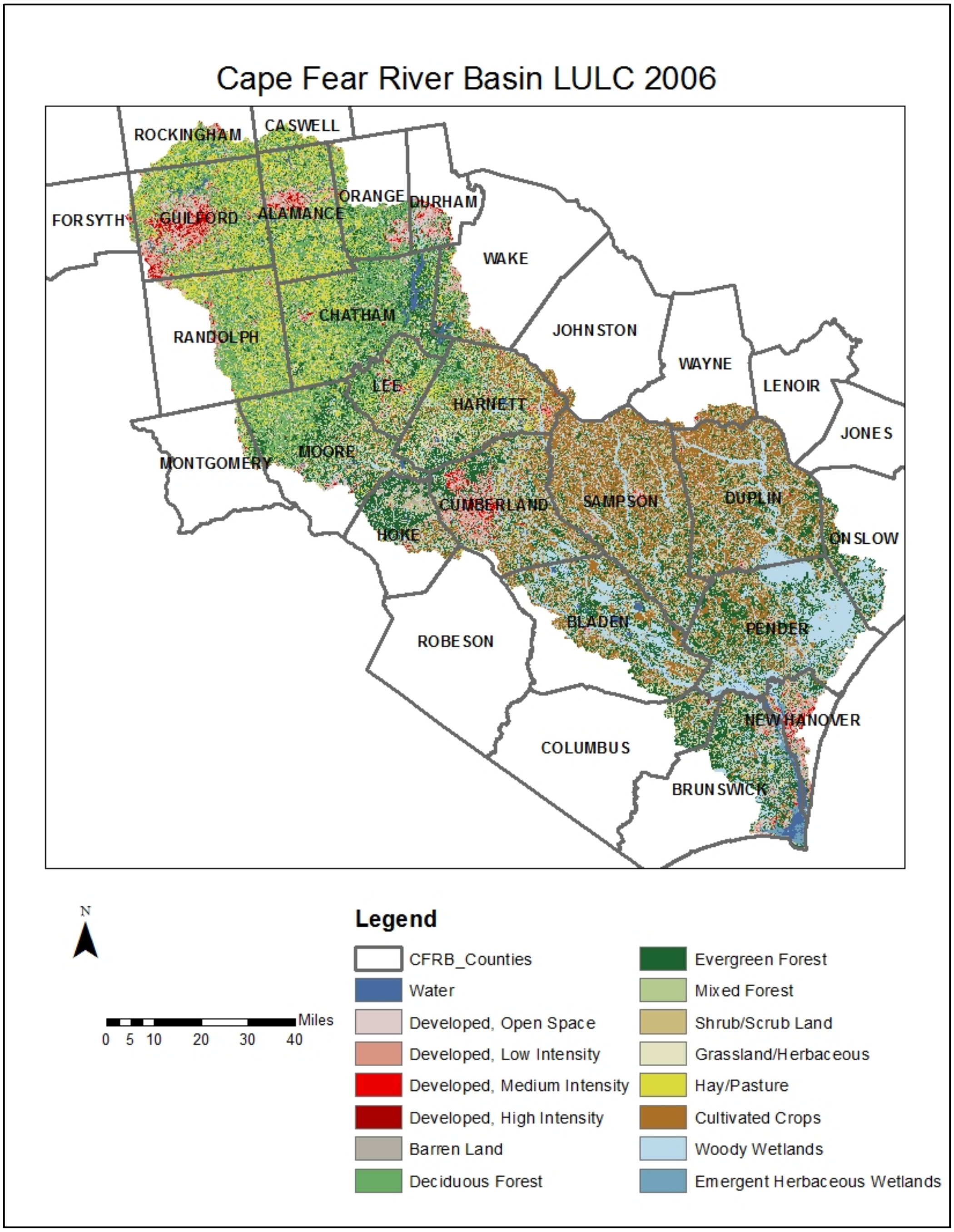

Figure 12. Land-Use/Land-Cover Types Across the Cape Fear River Basin, 2006.

Although understanding and spatial illustrating relationships between land types and water quality at the river basin scale is the primary purpose of this study, as Rothenberger et al. (2009) highlighted, there can be significant differences in these relationships at each of the physiographic region scales. Understanding how these regional difference compare to findings at the river basin scale may assist resource agencies in developing more comprehensive river basin plans and policies that highlight the spatial characteristics of water quality trends at multiple geographical scales.

Upper Cape Fear River Basin

The Upper Cape Fear River Basin (UCFRB) is located in the piedmont region of central North Carolina and is largely characterized by sprawling cities surrounded by agricultural and forested landscapes. At the river basin scale, the UCFRB was identified as the region that contained the largest percentage of water quality monitoring stations that exceeded the NC DENR fecal guidelines from October 2000 to 2001 (i.e. 2001) (84%) and from October 2006 to October 2007 (i.e. 2006) (56%). Fecal coliform trends in the UCFRB will be discussed in more detail later in this section. As noted in the previous section, a majority of the literature has linked increases in fecal concentrations in surface water systems with urban and agricultural areas, although, in much smaller concentrations, disturbed forested landscapes may also contribute to this increase.

Annual averages of the remaining water quality parameters reveal that none of the stations in the UCFRB exceeded NC DENR guidelines or EPA recommendations for DO and NH_3-N in 2001, however, UCFRB station 39 exceeded the EPA recommendation for point source pollution for phosphorus (P) in both years (2.14 mg/L 2001, 1.07 mg/L 2006) (Tables 5 and 6). The watersheds draining to UCFRB station 6, which is inclusive of UCFRB station 5, included nutrient sensitive and water supply surface water systems and thus exceeded

NC DENR guideline for nitrate-nitrite nitrogen (NO2-NO3) in 2006 (12.54 mg/L) (Tables 5 and 6). In addition, UCFRB station 22 represented the highest annual average for NO2-NO3 (9.22 mg/L) and UCFRB station 6 represented the highest annual average for NH3-N (0.82 mg/L) at the river basin scale. In 2006, UCFRB 6 represented the highest annual average for NO2-NO3 (12.54mg/L), exceeding both the NC DENR guideline and EPA recommendation, and UCFRB 25 represented the highest annual average for NH3-N (0.32 mg/L) across the river basin and within the UCFRB.

In relation to the spatial distribution of LULC types, the UCFRB is the most urbanized physiographic region in the CFRB with development representing 15 percent of the total landscape. Many of these urban areas encompass streams and tributaries that serve as the headwaters of the Cape Fear River. Although the UCFRB region is the most urbanized, development is highly concentrated and primarily consisted of exurban development (8% km2) and low intensity development (4% km2) resulting in spatially dispersed development patterns radiating from city centers. Concentrations of urban areas occurred in central and western Guilford and Alamance counties, eastern Orange County, and western Durham County. In contrast, agriculture (27% km2) and forest (47% km2) were the most spatially extensive land types with hay/pasture (22% km2) and deciduous forest (36% km2) largely representing this physiographic region (Figures 12, 13, 14, 15). In addition, UCFRB had the highest concentration of state and federal permitted cattle operations/facilities in the CFRB (Figure 2). When considering landscape changes across the UCFRB from 2001 to 2006, development increased by 0.52 percent and agricultural land increased by 0.62 percent, which signifies that while there was variation in the water quality parameters there was little change in the landscape.

Table 5. 2001 Descriptive Statistics for the Annual Averages of Water Quality Parameters for Stations Located in the Upper CFRB. n = 31

Water Quality Parameters	Minimum	Maximum	Mean	Standard Deviation	Number of Stations with Annual Averages Exceeding State/EPA Guidelines
Fecal coliform (col/100ml)	85	3,618	716	917	16
DO (mg/L)	6.06	9.08	7.92	0.76	0
NO2-NO3 (mg/L)	0.10	9.22	2.10	2.33	0
NH3-N (mg/L)	0.03	0.82	0.15	0.18	0
P (mg/L)	0.03	2.14	0.37	0.40	1

Table 6. 2006 Descriptive Statistics for the Annual Averages of Water Quality Parameters for Stations Located in the Upper CFRB. n = 31

Water Quality Parameters	Minimum	Maximum	Mean	Standard Deviation	Number of Stations with Annual Averages Exceeding State/EPA Guidelines
Fecal coliform (col/100ml)	42	1,472	402	369	13
DO (mg/L)	6.42	10.65	8.65	1.00	0
NO2-NO3 (mg/L)	0.09	12.54	2.22	3.13	2
NH3-N (mg/L)	0.03	0.32	0.07	0.06	0
P (mg/L)	0.03	1.07	0.22	0.23	1

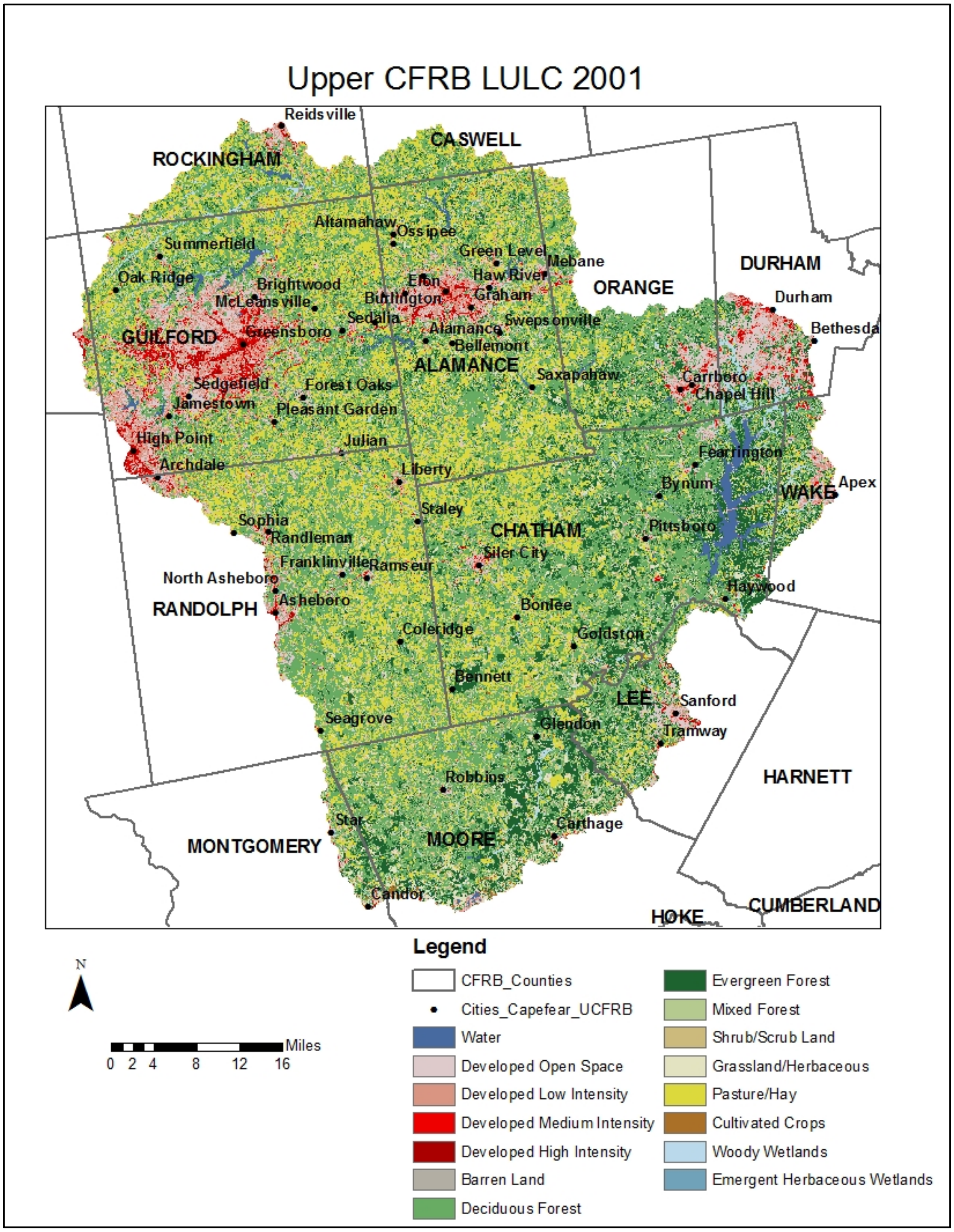

Figure 13. Land-Use/Land-Cover Types Across the Upper CFRB, 2001.

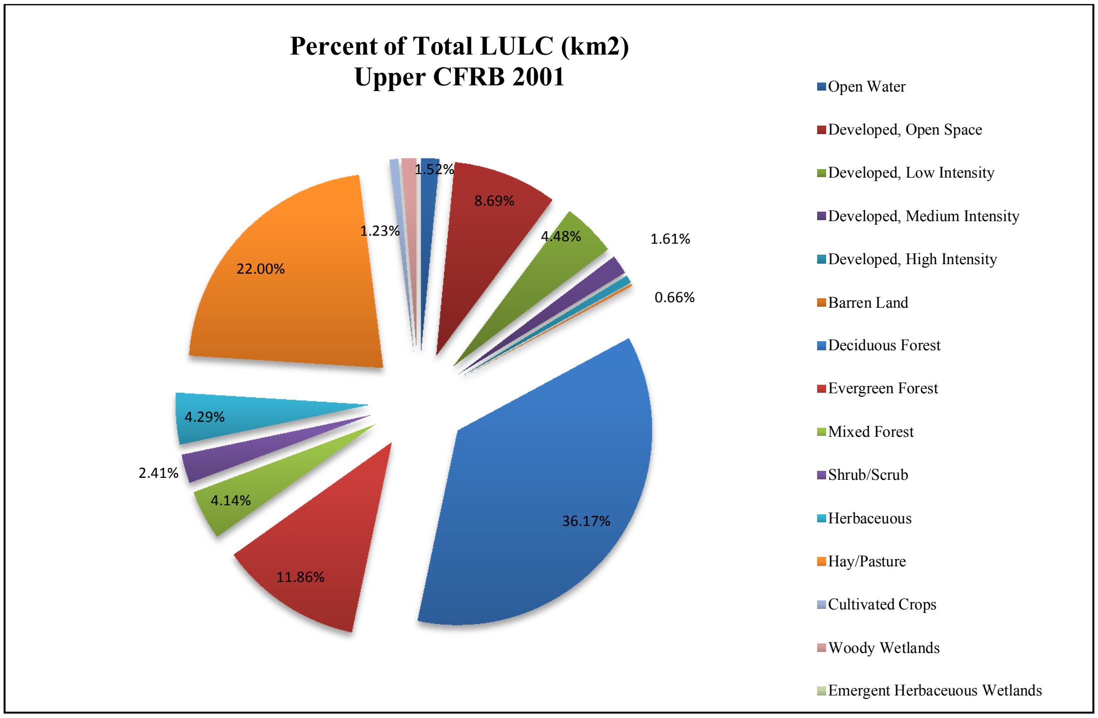

Figure 14. Percent of Total Land-Use/Land-Cover Types, Upper CFRB 2001.

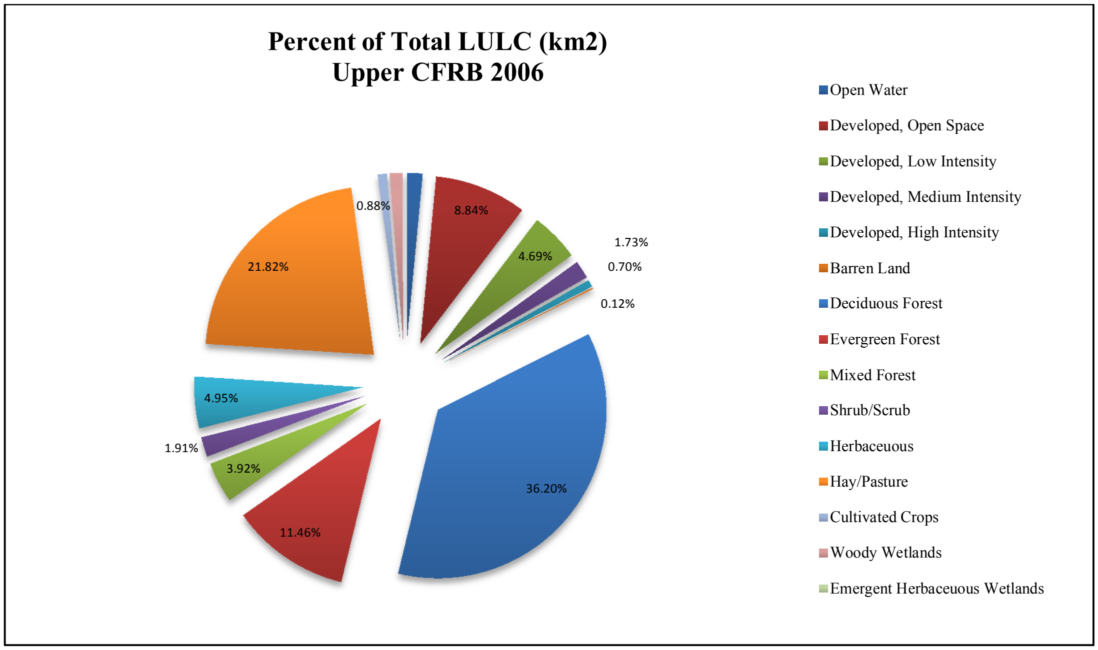

Figure 15. Percent of Total Land-Use/Land-Cover Types, Upper CFRB 2006.

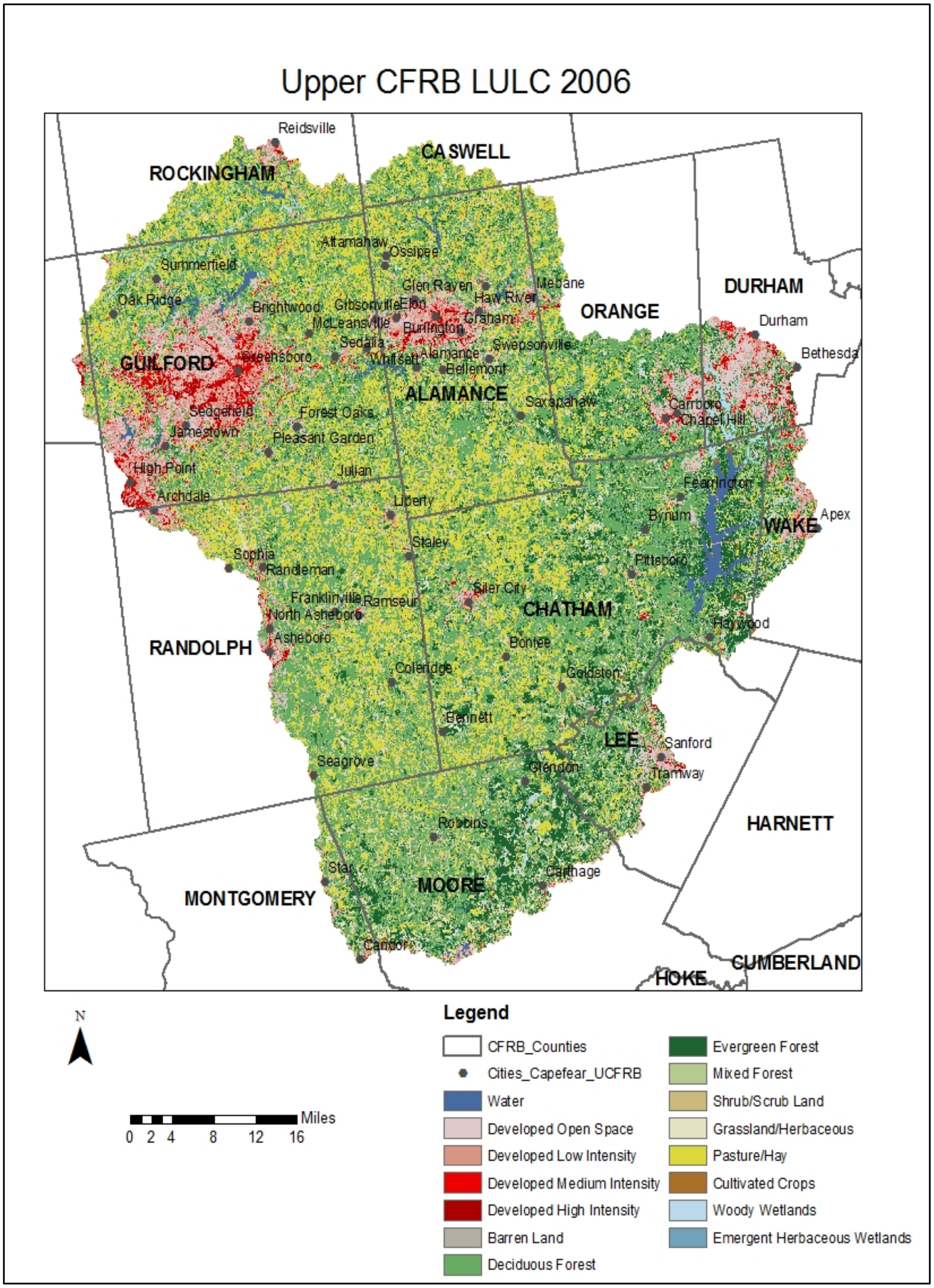

Figure 16. Land-Use/Land-Cover Types Across the Upper CFRB, 2006.

UCFRB: Fecal Coliform

High concentrations of *Fecal coliform* as well as drastic increases and decreases in fecal have been identified at multiple stations in the UCFRB from October 2000 to 2001 (i.e. 2001) and from October 2005 to 2006 (i.e. 2006). Figure 17 illustrates changes from 2001 to 2006 for each of the monitoring stations under observation in this study. The UCFRB represented the physiographic region with not only the highest recorded fecal concentrations across the river basin, but it is also the region with the most extreme changes in fecal counts from 2001 to 2006.

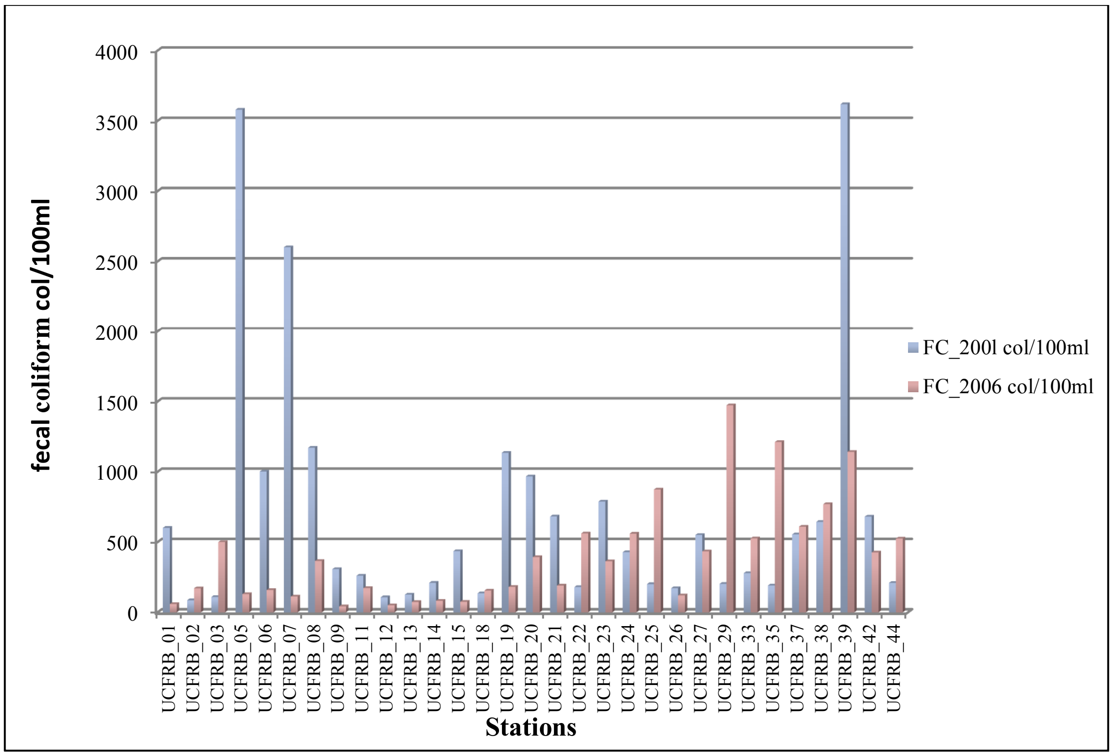

Figure 17. Changes in Fecal Coliform from October 2000 to October 2001 to October 2006 to October 2007 for Stations Included in this Study Located in the Upper CFRB.

In 2001, UCFRB station annual averages for fecal coliform ranged from a low of 85 col/100ml to a high of 3,618 col/100ml with an annual mean of 716 col/100ml (Table 7). In addition to representing the highest annual average for fecal from October 2000 to October 2001, UCFRB 39 represented the highest geometric mean for fecal both at the river basin scale and within the UCFRB during the study period. Station 39 is located in Montgomery County and drains a single watershed characterized by a mixed landscape pattern of exurban development (17% km2), deciduous forest (28% km2), and hay/pasture (27% km2) (Figure 18). Spatially, exurban development occurred in the northern and western portions of the watershed, while hay/pasture were largely located in the central and southeastern portions of the watershed. In contrast, deciduous forest was highly dispersed throughout the watershed. From 2001 to 2006 here were no changes in development, a 0.77 percent decrease in forestland, and a 1.80 percent increase in agricultural land. Ten of the monthly samples taken from this station in 2001 exceeded the NC DENR guideline for fecal. The most extreme spikes in fecal occurred from October 2000 (460 col/100ml) to November 2000 (5,200 col/100ml) and from December 2000 (5,800 col/100ml) to January 2001 (13,600 col/100ml). From 2001 to 2006, the annual average of fecal counts in this watershed decreased from 3,618 col/100ml to 1,140 col/100ml. Total annual precipitation slightly decreased from 2001 (39 inches) to 2006 (37 inches) with the highest totals occurring in March, May and June. There does not appear to be a temporal alignment between monthly rainfall totals and monthly fecal spikes, so one may speculate that surface runoff from the landscape alone may not be a significant factor in changes related to fecal concentrations in this watershed. Since the water quality stations do not monitor stream flow, it is beyond the scope of this study to identify relationships between precipitation patterns, surface runoff, and trends in fecal concentrations. Although there are no CAFOs located in this watershed, a large majority of the landscape is represented by hay/pasture and forestland that typically support livestock operations and wildlife populations. Activities associated with hay/pasture land may include livestock occupying sizeable swaths of land, which may result in large amounts of fecal being deposited onto the landscape and later conveyed to nearby streams by attaching to eroded soil particles. Other landscape features in this watershed include the Town of Star's WWTP which is located 1.27 miles upstream from station 39. When reviewing the NC DENR Sanitation Sewer Overflow (SSO) reports, this WWTP was vandalized resulting in 5,000 gallons of raw sewage being spilled in October 2001. Although the report notes that this spill did not reach surface waters, individual rainfall events during this time may have resulted in this material entering local surface water systems since fecal can bind to soils that can be transported to nearby surface water systems.

In 2006, annual averages of fecal concentrations for stations located in the UCFRB ranged from a low of 42 col/100ml to a high of 1,472 col/100ml with an annual mean of 402 col/100ml. UCFRB station 29 (Figure 19) represented the highest annual average for fecal from October 2006 to October 2007 in both the UCFRB and for the entire CFRB. Located in western Guilford County, development, which included 24 percent exurban development, 23 percent low intensity, 9 percent medium intensity, and 4 percent high intensity accounted for 56 percent this watershed's landscape. Within this watershed, development beyond the urban core was concentrated in and around the cities of Greensboro, Jamestown, and High Point and along the interstate 40 and 85 corridors. Agricultural land (13% km2) were predominantly represented by hay/pasture and were primarily located in the northwestern portion of the watershed. Although there were no permitted animal feeding operations located in this watershed, this watershed contains agricultural land largely represented by hay/pasture that may contain large amounts of fecal from livestock. In addition, there were 13 NPDES permitted facilities that are largely represented by wastewater treatment facilities.

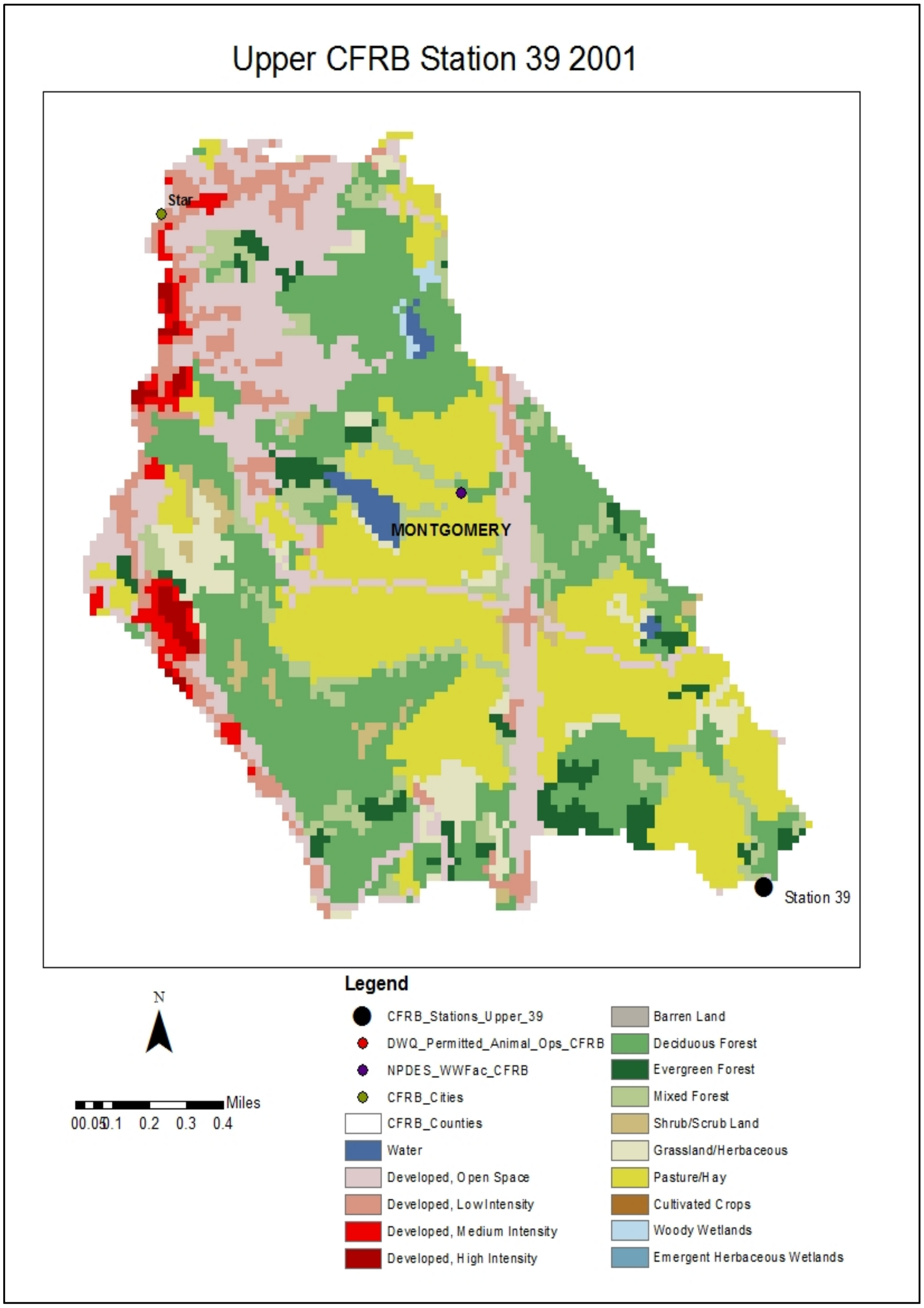

Figure 18. Land-Use/Land-Cover Types Draining to UCFRB Station 39, 2001.

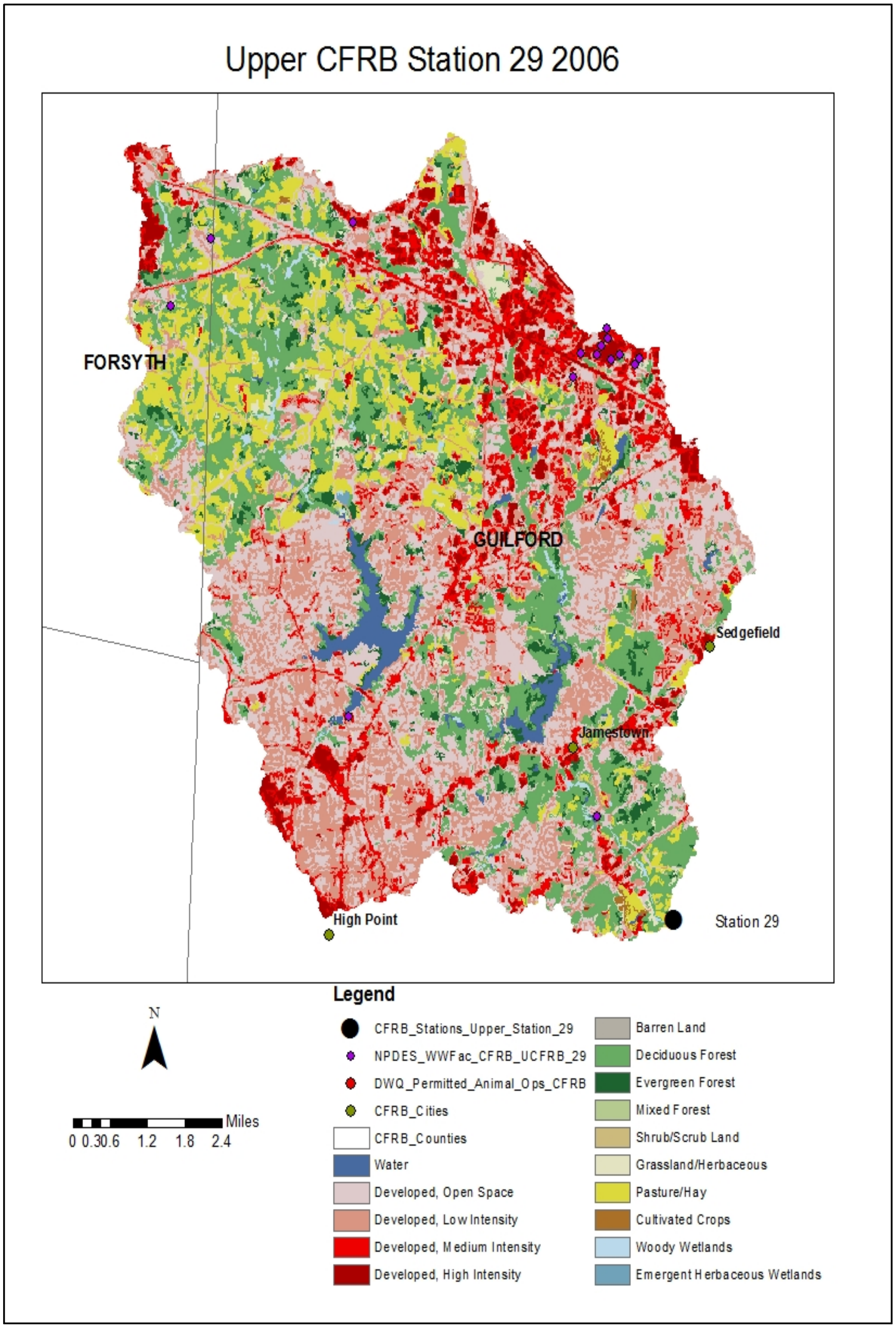

Figure 19. Land-Use/Land-Cover Types Draining to Upper CFRB Station 29, 2006.

When reviewing NC DENR SSO incident reports, none of the permitted facilities located in this watershed reported major spills. Although there were no WWTP incidents reported from 2006 to 2007, potential fecal sources within this watershed may include undetected leaks from wastewater sewer pipes and domestic pet and wildlife feces being conveyed to surface waters by stormwater infrastructure, which may have collectively contributed to the fecal patterns exhibited in this watershed in 2006.

Changes in fecal counts from 2001 to 2006 at station 29 included a 1,270 col/100ml increase with large monthly increases occurring during the fall and spring months. Three of this station's monthly samples exceeded state guidelines for fecal in both years. Regarding landscape changes from 2001 to 2006 there was a 2.68 percent increase in development that included a 0.68 percent increase in exurban development, a 1 percent increase in low intensity, a 0.72 percent increase in medium intensity, and a 0.28 percent increase in high intensity development. In contrast, forest and agricultural land decreased by 1.85 percent and 0.85 percent respectively. When observing precipitation patterns from 2001 to 2006, total precipitation increased from 31 to 36 inches, with the largest rainfall occurring in March and July 2001 and April 2006.

Although stations 39 and 29 had different land types and patterns, the literature has demonstrated that each of the land types that comprise these watersheds have a positive association with increases in fecal coliform. Since there is little change in landscape and precipitation and no permitted animal feeding operations located in these watersheds one must consider alternative sources of fecal that may not be represented by LULC type or climatic patterns alone. For example, since station 39 drains a watershed largely dominated by agricultural and forested land, fecal concentrations may come from failed septic systems, livestock or domesticated horse grazing and or wildlife waste that may have entered streams through surface runoff processes. In contrast, station 29 drains a watershed comprised largely of development. One potential explanation of high fecal concentrations in this urbanized watershed may come from wastewater treatment plants (WWTPs) infrastructure spills or leaks as supported by the SSO reports and or domestic pet waste entering surface water systems through stormwater runoff processes.

Other significant changes in fecal coliform from 2001 to 2006 in the UCFRB occurred at stations 05, 07, 29, 35, and 39 with increases occurring at stations 29 and 35 (Figure 16). Out of these five stations, station 35 is the only one that is nested indicating a potential cumulative influence of land activities upstream of this station in regards to increases in fecal coliform concentrations. The annual average of fecal coliform at this station increased from 191 col/100ml to 1,211.17 col/100ml with major increases occurring during the fall and spring months. When considering stations that drain individual watersheds, UCFRB station 29 experienced the largest increase and UCFRB station 05 experienced the largest decrease in fecal coliform from 2001 to 2006. Since the cumulative effects of land types within nested watersheds on fecal counts at station 35 are difficult to identify and fecal trends at station 29 have already been discussed in detail the remainder of this section will focus on UCFRB station 05.

Station 05 represented the station in the UCFRB that exhibited the largest decrease in fecal concentrations from 2001 and 2006 (Figures 20). The annual average of fecal coliform at this station decreased drastically from 3,578 col/100ml in 2001 to 129 col/100ml in 2006. During this time period, the annual average for precipitation slightly increased from 30 to 31 inches indicating that on an annual basis total precipitation did not vary much within this watershed. In addition, state permitted animal feeding operations are not located within this watershed. Seven of this station’s monthly samples exceeded NC DENR guidelines from October 2000 to October 2001, while none of the samples exceeded this guideline from October 2006 to October 2007. Significant increases in fecal in 2001 occurred in November and December (12,000 col/100ml) and September (14,800 col/100ml). In contrast, in 2006 the largest monthly fecal concentration occurred in the spring (i.e. May 2007 300 col/100ml). This watershed is located in central Guilford County, includes the City of Greensboro, and is northeast of the watershed draining to station 29. Development largely characterized this watershed in both 2001 and 2006. For both years the landscape in the watershed included approximately 37 percent exurban development, 37 percent low intensity development, 15 percent medium intensity development, and 9 percent high intensity development (Figure 19). Collectively these development comprised 98 percent of this watershed. Although miniscule, development increased by 0.19 percent while forestland decreased by 0.19 percent and agricultural land remained unchanged from 2001 to 2006. From 2006 to 2007 an estimated 404,000 gallons of raw sewage reached surface waters in the City of Greensboro, which largely represents this watershed, which was almost double the amount reached surface waters in 2001 (i.e. 257,457). Although this is a significant amount, there is no flow data associated with the fecal samples so it is difficult to determine if precipitation events may have diluted fecal concentrations.

The relationship between impervious surfaces and fecal coliform experienced at stations 29 supports a growing body of literature that has successfully linked these relationships at different geographical scales. This may be due to the fact that impervious surfaces (e.g. roads, rooftops, sidewalks, etc.) that characterize developed areas typically convey non-point sources of pollution, such as fecal coliform bacteria, at faster rates and higher concentrations directly to surface water systems through stormwater infrastructure systems (e.g. stormwater drains located along the edges of streets). Given that so many documented sewer spills have occurred in cities located in this watershed, it may be difficult to determine if point sources of pollution are masking relationships between LULC types and water quality. When considering the different types of development, this watershed is largely characterized by development with low percentages of impervious surfaces (e.g. low intensity development or exurban development). As Mallin et al. (2001) observed, sprawling development patterns might encompass more total impervious surface when compared high intensity development because development patterns are highly dispersed throughout the watershed. Since there was only a slight change in development in the UCFRB it is likely that the drastic increase in fecal counts were attributed to a combination of events including WWTPs leaks or spills, the presence of domestic pet waste as well as the high percentage of existing development with infrastructure that can convey fecal concentrations to nearby surface water systems.

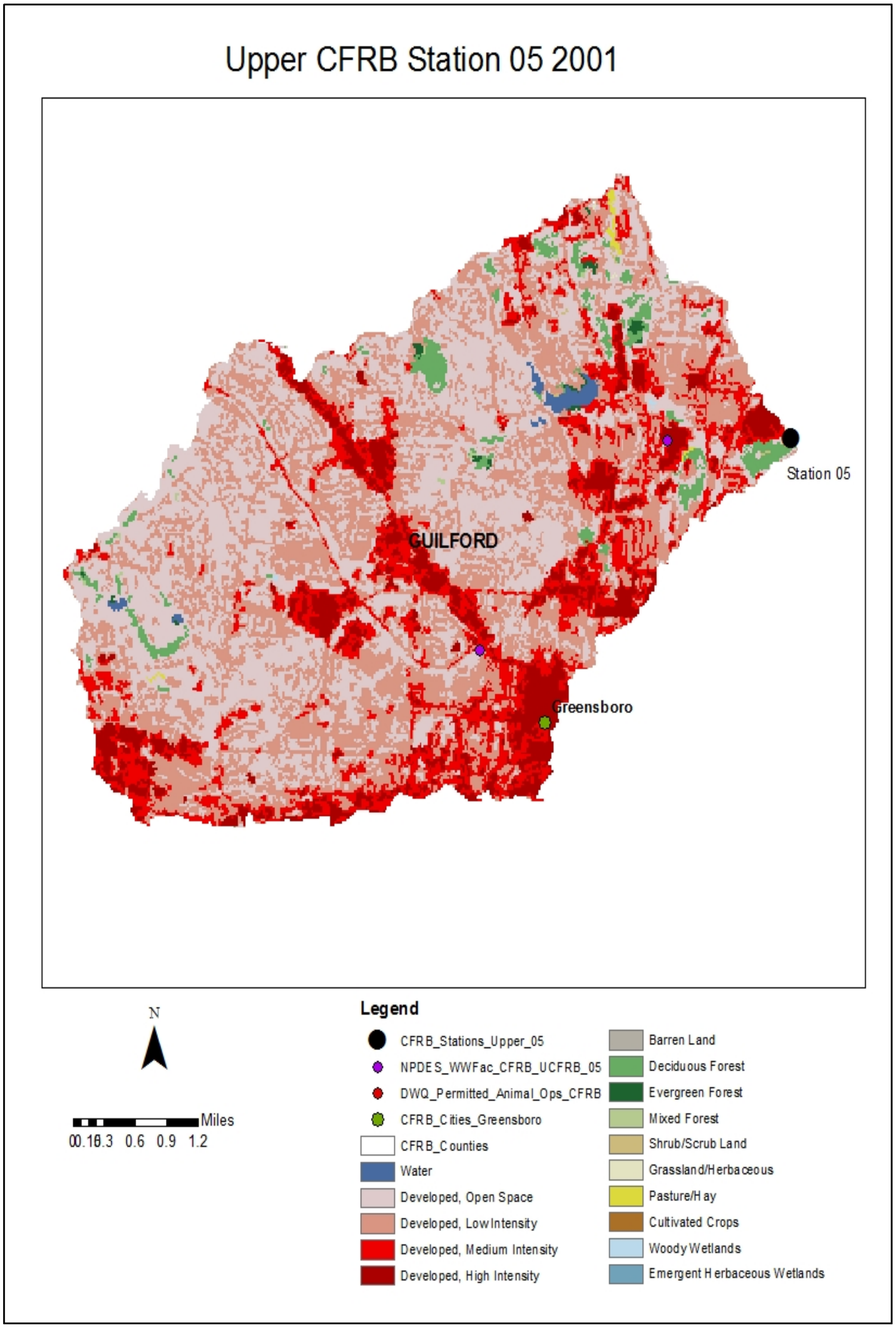

Figure 20. Land-Use/Land-Cover Types Draining to UCFRB Station 05, 2001.

Middle Cape Fear River Basin

The Middle CFRB (MCFRB) embodies a transitional landscape from the lower Piedmont to the Sandhills regions of North Carolina. This physiographic region is the smallest region in the basin and includes portions of Moore, Wake, Lee, Harnett, Hoke, Cumberland, Bladen, and Columbus counties. Like the UCFRB, fecal coliform signified the highest amount of variability among the water quality parameters under investigation as well as the only parameter that exceeded state guidelines and EPA recommendations for both years. One will note that while the highest recorded concentration of fecal from October 2000 to 2001 (i.e. 2001) was 2,145 col/100ml, from October 2006 to October 2007 (i.e. 2006) the highest value was significantly lower (729 col/100ml) (Tables 7 and 8).

Table 7. 2001 Descriptive Statistics for the Annual Averages of Water Quality Parameters for Stations Located in the Middle CFRB. n = 21

Water Quality Parameters	Minimum	Maximum	Mean	Standard Deviation	Number of Stations with Annual Averages Exceeding State/EPA Guidelines
Fecal coliform (col/100ml)	18	2,145	281	497.21	3
DO (mg/L)	7.73	10.45	8.99	0.54	0
NO2-NO3 (mg/L)	0.06	1.48	0.63	0.35	0
NH3-N (mg/L)	0.03	0.13	0.07	0.02	0
P (mg/L)	0.04	0.39	0.18	0.09	0

Table 8. 2006 Descriptive Statistics for the Annual Averages of Water Quality Parameters for Stations Located in the Middle CFRB. n = 21

Water Quality Parameters	Minimum	Maximum	Mean	Standard Deviation	Number of Stations with Annual Averages Exceeding State/EPA Guidelines
Fecal coliform (col/100ml)	24	729	238.	210.07	6
DO (mg/L)	6.52	10.14	8.20	0.73	0
NO2-NO3 (mg/L)	0.10	1.23	0.66	0.33	0
NH3-N (mg/L)	0.03	0.10	0.05	0.02	0
P (mg/L)	0.03	0.33	0.14	0.07	0

When observing the spatial distribution of land types in the MCFRB, forest and agricultural land are highly dispersed and dominated most of the landscape, while development was highly concentrated. Development primarily occurred in and around the City of Fayetteville in Cumberland and Hoke counties. This area of the MCFRB serves as the largest and most sprawling urban center largely due to the presence of Fort Bragg Military Base. Changes in the MCFRB's landscape from 2001 to 2006 included increases in cultivated crops (1.21% km2), low intensity development (0.27% km2), exurban development (0.25% km2), and medium intensity development (0.12% km2). Decreases in land types included woody wetlands (0.27%), herbaceous grassland (0.27%), mixed forest (0.23%), and shrub/scrub land (0.17%). Overall, development increased by 0.66 percent, which was principally driven by increases in exurban and low intensity development. As a result, this region represents the highest increase in development when compared to the UCFRB and the LCFRB. In addition, agricultural land increased by 0.85 percent, which was largely characterized by an increase in cultivated cropland. Although there was little change in LULC types, there was a significant decrease in fecal through this region during the study period (Figures 21, 22, 23, 24).

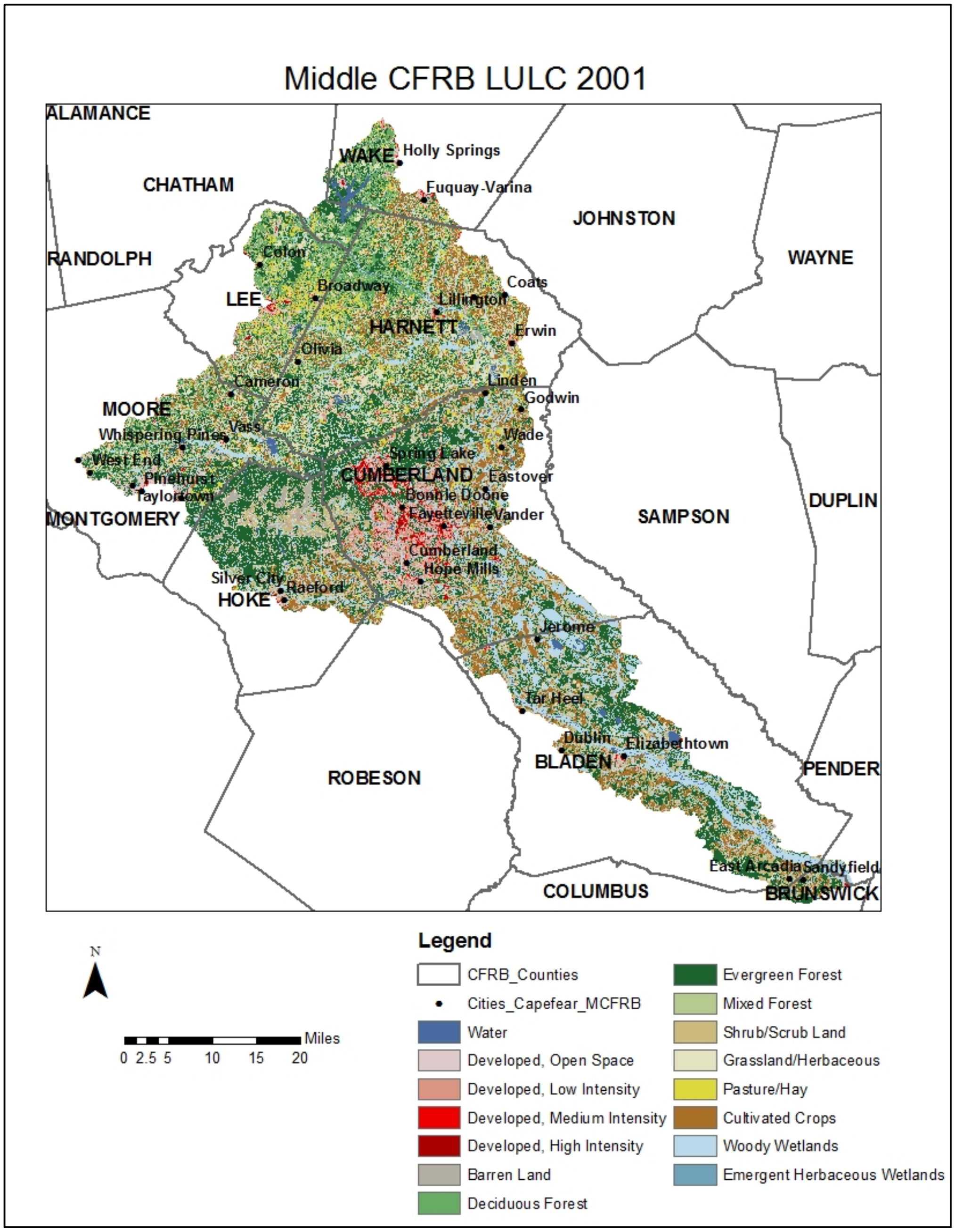

Figure 21. Land-Use/Land-Cover Types in the Middle CFRB, 2001.

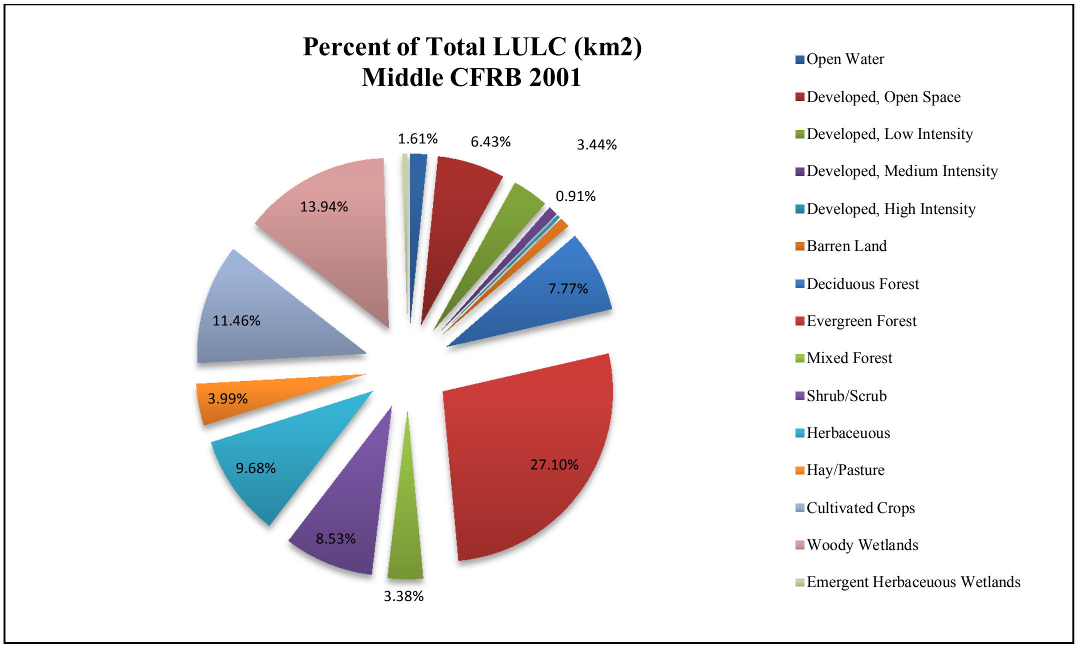

Figure 22. Percent of Total Land-Use/Land-Cover Types, Middle CFRB 2001.

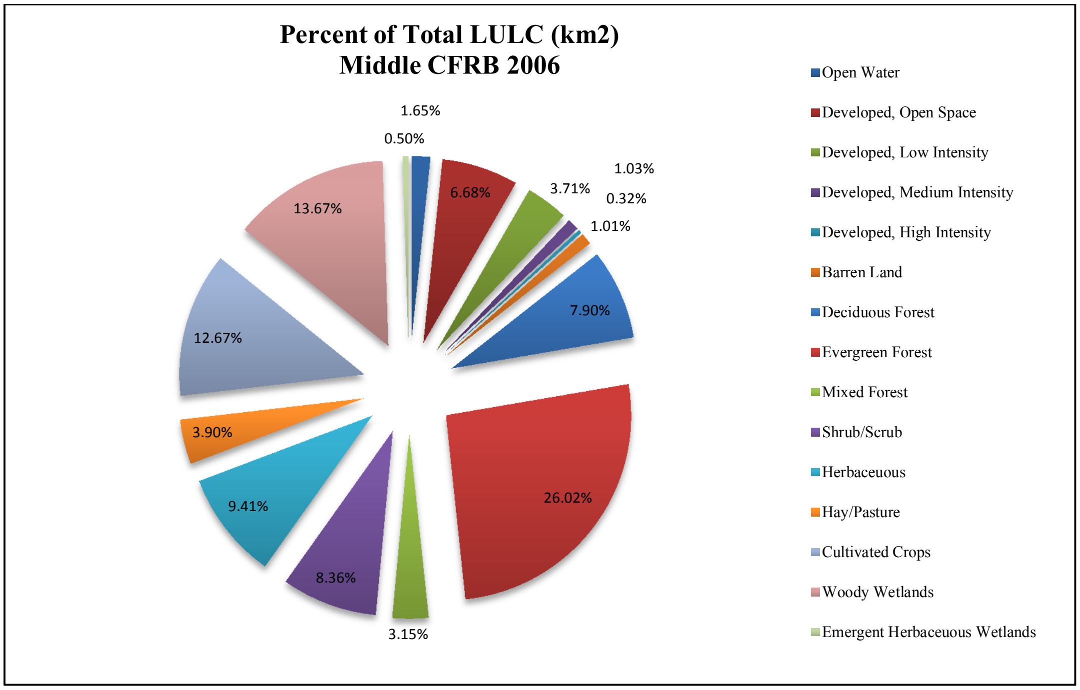

Figure 23. Percent of Total Land-Use/Land-Cover Types, Middle CFRB 2006.

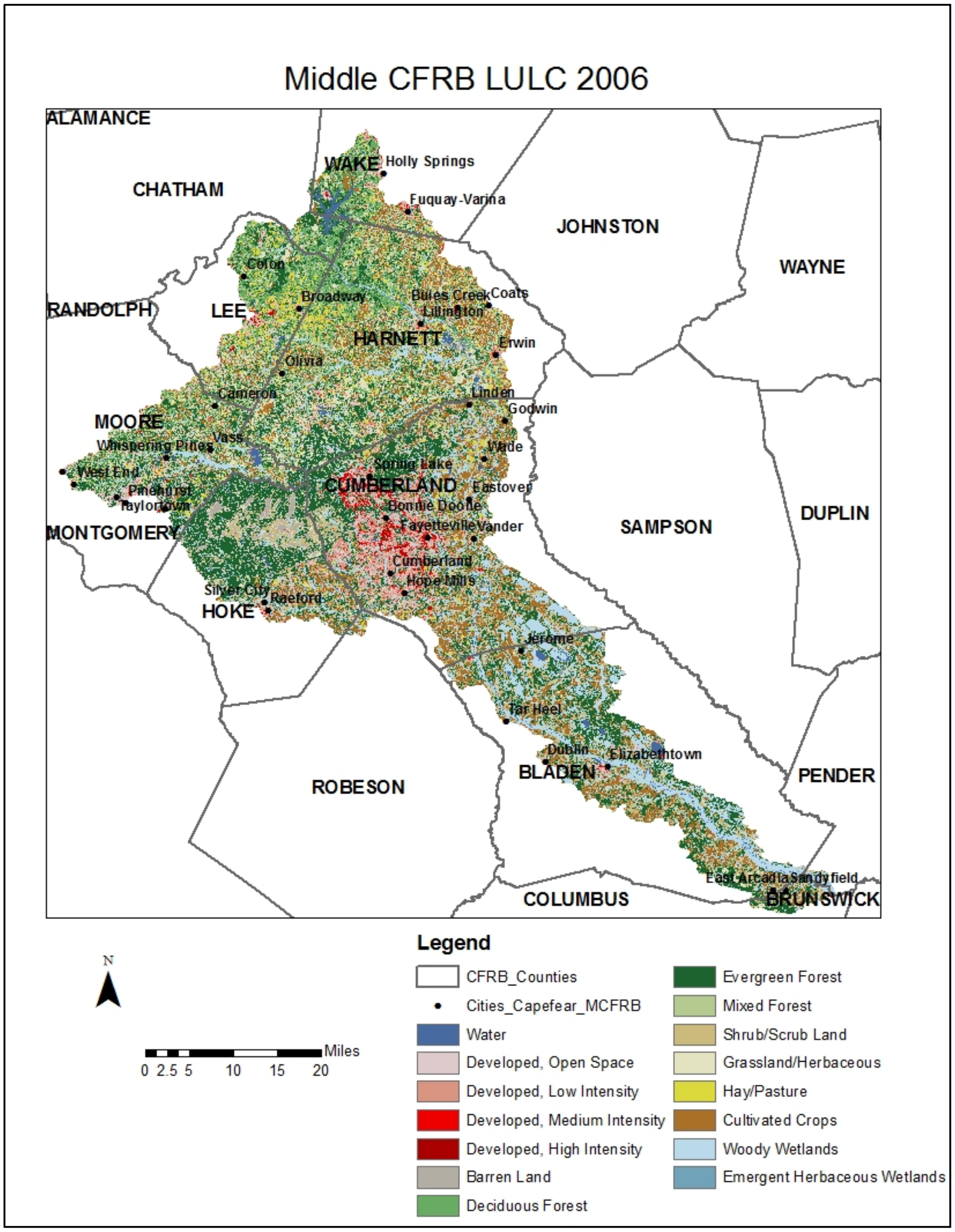

Figure 24. Land-Use/Land-Cover Types Across the Middle CFRB, 2006.

MCFRB: Fecal Coliform

Although not as drastic as the UCFRB, overall, annual averages of stations located in the MCFRB experienced a 1,416 col/100ml decrease in fecal coliform from October 2000 to October 2001 (i.e. 2001) and from October 2006 to October 2007 (i.e. 2006) (Tables 7 and 8). Figure 25 illustrates changes in fecal concentrations for each of the stations located in the MCFRB region. Three stations (MCFRB 08, 10, 12) exceeded state fecal guideline in 2001, while six stations (MCFRB 01, 04, 07, 12, 22, and 23) exceeded the state guideline in 2006. Station 12 exceeded the state guideline for fecal in both years, despite a decrease in fecal counts from 728 col/100 ml in 2001 to 586 col/100 ml in 2006. All of these stations, except stations 12, 07, and 23, drain multiple watersheds upstream of their location including all of the watersheds that comprise the UCFRB. When applying the geometric mean to MCFRB station monthly fecal data, one will observe that none of the stations exceeded this state guideline in 2001 and MCFRB 12 was the only station that exceeded the guideline in 2006. Given the fecal trends in the UCFRB previously discussed, it is not surprising that nested stations located in the MCFRB that drain watersheds in the UCFRB experienced high concentrations of fecal coliform bacteria.

In 2001, station annual averages for fecal coliform ranged from a low of 18.17 col/100ml to a high of 2,145 col/ml with an annual mean of 281 (Table 7). MCFRB station 10 represented the highest annual average for fecal in 2001, however, this station drains multiple watersheds located in both the UCFRB and MCFRB so it is difficult to isolate trends in fecal concentrations that are unique to the MCFRB region. Given this limitation, station 12 represented the only station that drains an individual watershed that exceeded the state guideline for fecal for 2001 and 2006. Located southwest of the City of Fayetteville and inclusive of portions of Fort Bragg Military Base in Hoke County, station 12 drains a watershed that included 45 percent forestland, 14 percent agricultural land, 12 percent wetlands, and 10 percent development. In addition, there is a CAFO located 5.36 miles upstream that is permitted for 3,552 head of swine and the City of Raeford's WWTP is located 4.76 miles upstream from this station. Both of these activities have been linked to increases in fecal counts in nearby surface waters. The headwaters of this watershed are primarily located in Fort Bragg Military Base and these surface waters traverse several land types including forestland, barren land, agricultural land, and urban development before reaching station 12.

In 2001, five monthly samples at MCFRB station 12 exceeded fecal guidelines with March (1,300 col/100 ml), July (3,200 col/100ml), August (2,000 col/100 ml), and September (1,100 col/100 ml) representing the largest monthly fecal concentrations.

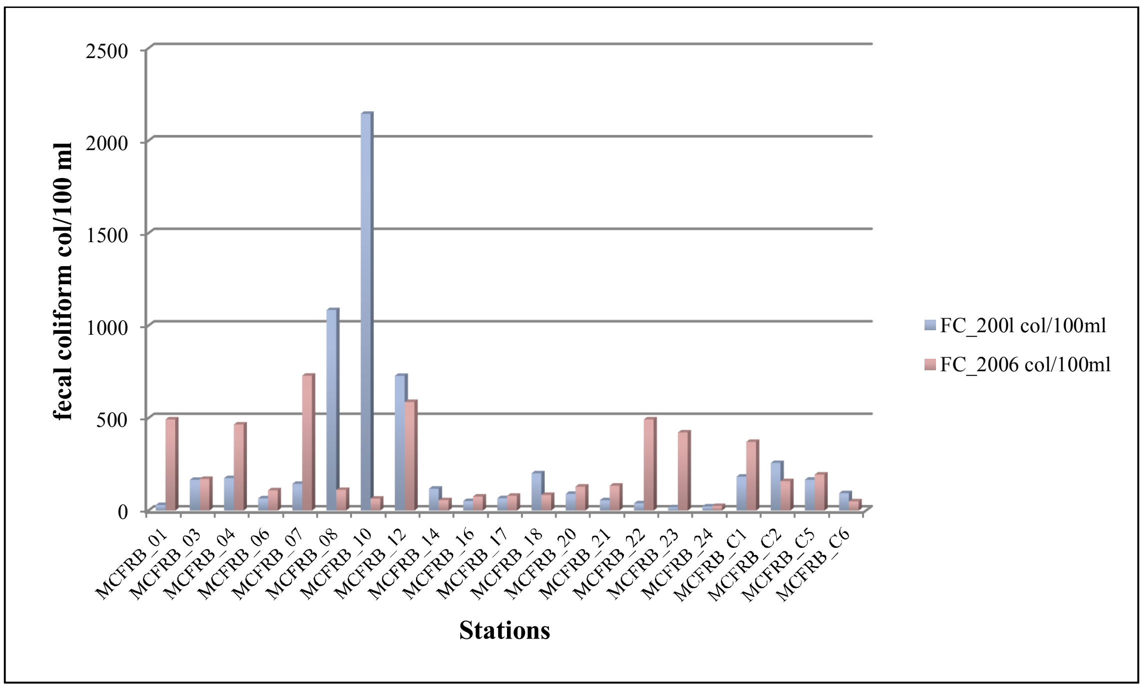

Figure 25. Changes in Fecal Coliform from October 2000 to October 2001 to October 2006 to October 2007 for Stations Included in this Study Located in the Middle CFRB.

Although there were no documented NC DENR SSO incidents, one may speculate that unidentified WWTP pipe leaks, the presence of CAFOs, and domestic pet waste from urban areas located upstream of station 12 may have collectively contributed to high fecal concentrations in 2001. In 2006, the annual average of fecal concentrations slightly decreased from 728 col/100ml to 586 col/100ml. November represented the only monthly samples in both years that exceeded state fecal guidelines, however, large increases occurred from February 2001 to March 2001 (+1,300 col/ 100ml) and from June 2007 to July 2007 (+2,400 col/100 ml). From 2001 to 2006 total precipitation increased from 32 to 40 inches. It is possible that the increase in total precipitation from 2001 to 2006 may have diluted the influence of fecal concentrations in this watershed and or changes in operations practices at the CAFO may have reduced the amount of fecal entering local surface waters. In addition, WWTP pipe leaks may have been addressed.

From 2001 (i.e. October 2000 to October 2001) to 2006 (i.e. October 2006 to October 2007), development (0.47% km2) and agricultural (0.07% km2) land increased in this watershed, while forestland decreased (0.23% km2). During this same time period, there was a slight decrease in fecal from 728 col/100 ml to 586 col/100 ml. The largest increase in development was represented by exurban development (+8% km2). Exurban development (i.e. Developed, Open Space) is defined as areas with a mixture of some constructed materials, but primarily consists of vegetation in the form of residential lawns, parks, golf courses and vegetation planted for developed settings. In addition, impervious surfaces account for less than 20 percent of the total land cover across this land type (Figure 3). Previous studies have linked similar landscape features to annual and seasonal increases in fecal concentrations from domestic pet waste (Mallin et al., 2001). In addition, retention ponds that may be located in these landscapes could attract wildlife, such a geese and wood ducks that may also contribute to increases in fecal concentrations. Since the landscape experienced little change, it is more likely that activities within this primarily forested watershed led to the decrease in fecal counts. As observed in previous studies (Ensign & Mallin, 2001; Line et al., 2008; and Cahoon et al., 2006), there could have been clear cutting activities, recreational uses such as horse riding trails, and/or septic system failures that could have caused elevated fecal concentration in 2001. In contrast, changes in CAFO activities, increases in precipitation, the establishment of vegetation and or the protection of bottomland forest could have resulted in the reduction of fecal bacteria in surface water systems in 2006 as observed by Mitsch et al. 2001 and others.

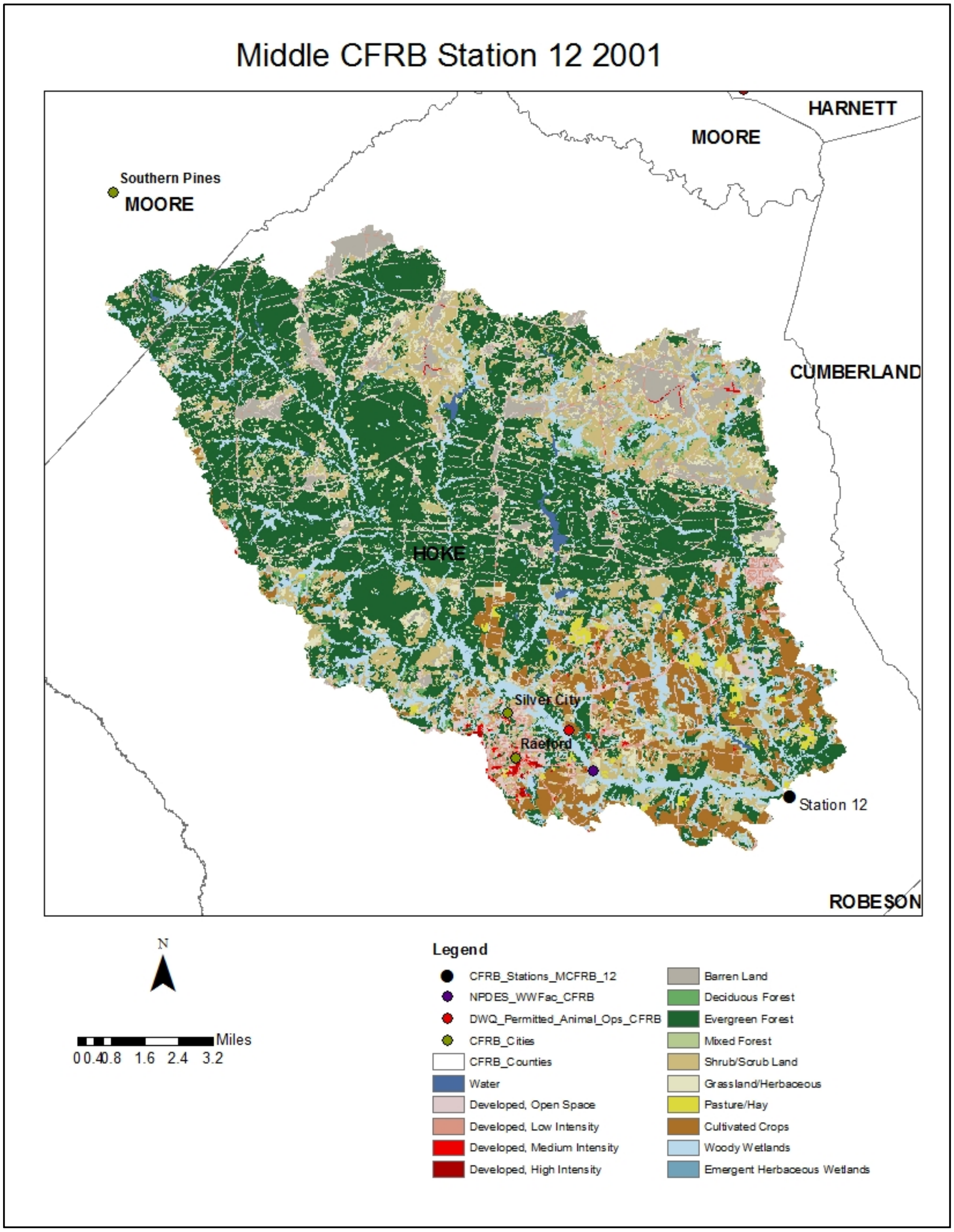

Figure 26. Land-Use/Land-Cover Types Draining to Middle CFRB Station 12, 2001.

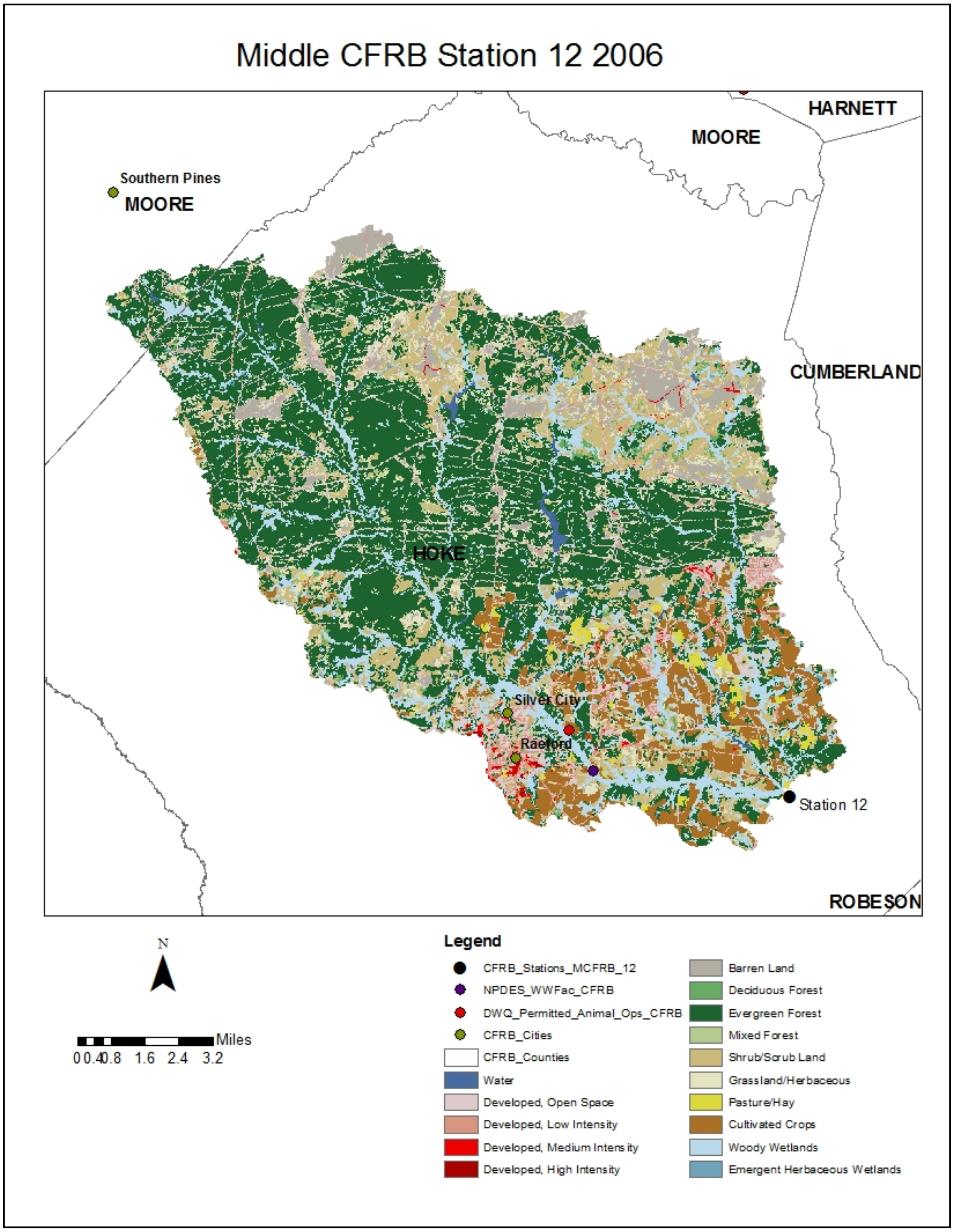

Figure 27. Land-Use/Land-Cover Types Draining to Middle CFRB Station 12, 2006.

Lower Cape Fear River Basin

The Lower Cape Fear River Basin (LCFRB) is characterized by a coastal plain landscape than contains blackwater and tidal estuarine systems. This region includes portions of Harnett, Johnston, Wayne, Lenoir, Onslow, Cumberland, Bladen, Brunswick, Pender, and New Hanover counties as well as all of Sampson and Duplin counties. Water quality trends in the LCFRB are unique compared to the UCFRB and the MCFRB because none of the stations under observation exceeded NC DENR guidelines or EPA recommendations for the water quality parameters under investigation in 2001 (i.e. October 2000 to October 2001) (Table 9). This is of particular interest when considering the dramatic and frequent fecal coliform exceedances for stations included in this study that took place in the UCFRB and MCFRB during this time period as well as the high numbers of CAFOs located in the LCFRB (Tables 5 and 7, Figure 2). Although none of the station's annual averages for fecal exceeded state guidelines, five of the stations (ROC, LRC, ANC, BCRR, and BC117) monthly samples exceeded the state guideline in 2001. One notable similarity among these five stations is that each of them exceeded the fecal guideline in March 2001. Although these stations are located in close proximity to one another, each of these stations drains a single watershed, so it may not be likely that a single event caused this occurrence at each of these stations. It should also be noted that while the watersheds draining to stations ROC, LRC, and ANC contain significant livestock headcounts and stations BCRR and BC117 do not contain any industrialized animal feeding operation facilities. In 2006, 20 percent of the LCFRB stations exceeded the state fecal guideline and only one station, LCFRB BC117, exceeded the EPA recommendation for phosphorus (P). When observing the monthly fecal samples at these stations, 11 stations had monthly samples that exceeded the state guideline for fecal, and five of these stations exceeded the guideline in both 2001 and 2006 (Tables 9 and 10).

Table 9. 2001 Descriptive Statistics for the Annual Averages of Water Quality Parameters for Stations Located in the Lower CFRB. n = 20

Water Quality Parameters	Minimum	Maximum	Mean	Standard Deviation	Number of Stations with Annual Averages Exceeding State/EPA Guideline
Fecal coliform (col/100ml)	29	261	89	66	0
DO (mg/L)	4.17	11.02	7.37	1.44	0
NO2-NO3 (mg/L)	0.05	7.13	0.64	1.53	0
NH3-N (mg/L)	0.06	0.26	0.10	0.04	0
P (mg/L)	0.06	0.97	0.18	0.19	0

Unlike the other physiographic regions, the LCFRB landscape includes a large portion of woody wetlands (24% km2) and the lower portion of this region experiences diurnal tidal patterns (i.e. two high and two low tides daily) that may dilute or flush out concentrations of pollutants. Wetlands have been linked to improved surface water quality however; excessive concentrations of pollutants can make these systems ineffective in removing pollutants (Verhoeven et al., 2006; Brinson, 1993; Fink et al., 2004; and Mitsch et al., 2001). The LCFRB is similar to the other physiographic regions in that it comprises forest and agricultural land that are largely dispersed throughout the basin, while development is primarily concentrated. Spatially, large extents of woody wetlands are located in the eastern portion of the basin in Pender County and to a lesser extent in western Bladen County. In contrast, development is highly concentrated in central and western New Hanover County along the Cape Fear River with a few smaller, but notable, developed areas in western and southern Brunswick County, southeastern Harnett County, and central Sampson County (Figures 28, 29, 30, 31).

Table 10. 2006 Descriptive Statistics for the Annual Averages of Water Quality Parameters for Stations Located in the Lower CFRB. n = 20

Water Quality Parameters	Minimum	Maximum	Mean	Standard Deviation	Number of Stations with Annual Averages Exceeding State/EPA Guideline
Fecal coliform (col/100ml)	41	1,448	271	344	4
DO (mg/L)	5.03	9.09	7.01	1.00	0
NO2-NO3 (mg/L)	0.06	5.92	0.59	1.26	0
NH3-N (mg/L)	0.03	0.10	0.06	0.02	0
P (mg/L)	0.07	1.72	0.21	0.36	1

The largest landscape changes across the LCFRB from 2001 to 2006 included an increase in cultivated crops (1.58% km2) and exurban development (0.12% km2), while decreases primarily occurred in shrub/scrub land (0.64% km2), evergreen forest (0.58% km2), and woody wetlands (0.39% km2). Agricultural land increased by 1.39 percent from 2001 to 2006, while development slightly increased from 5.84 percent to 6.11 percent (Figure 10).

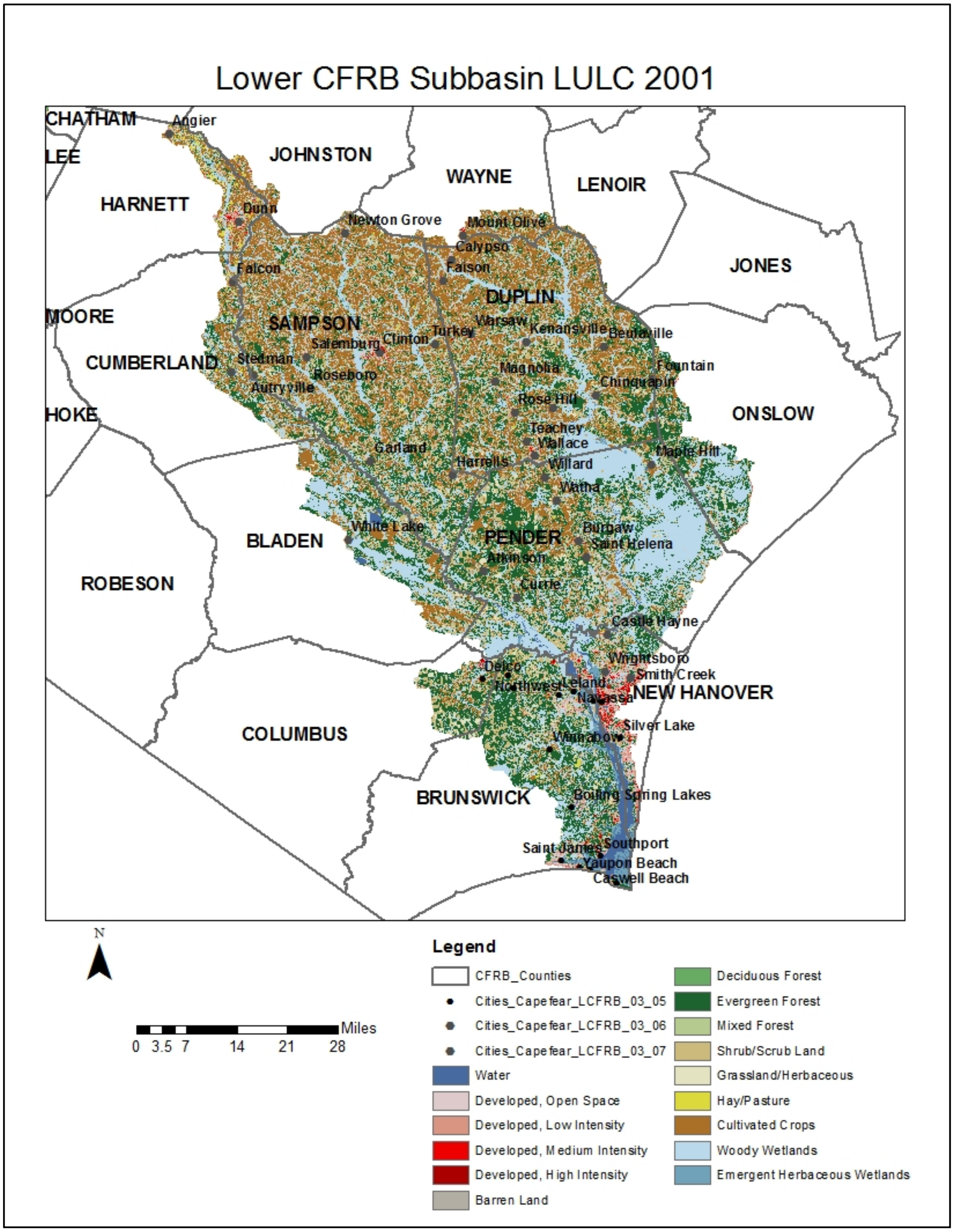

Figure 28. Land-Use/Land-Cover Types Across the Lower CFRB, 2001.

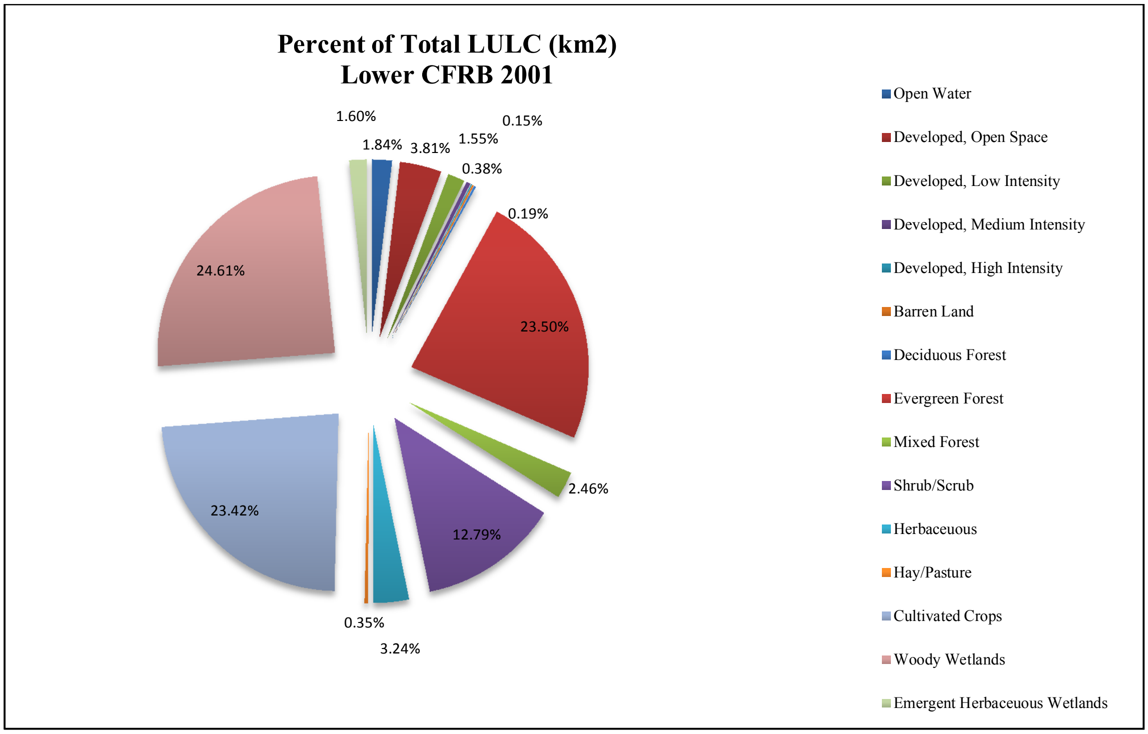

Figure 29. Percent of Total Land-Use/Land-Cover Types, Lower CFRB 2001.

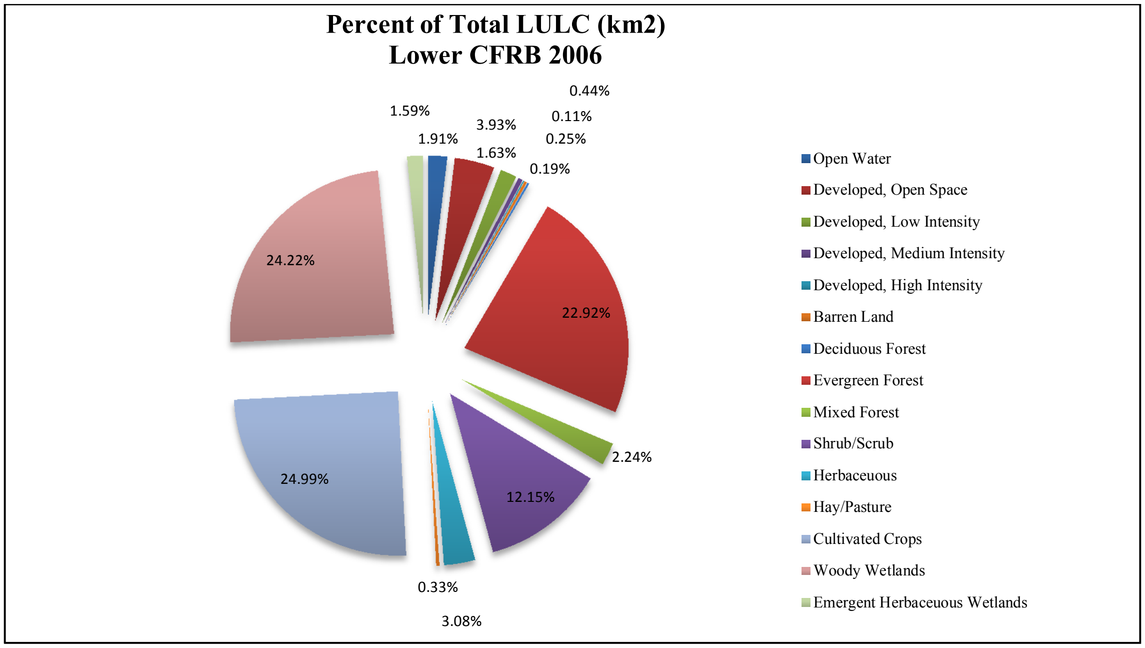

Figure 30. Percent of Total Land-Use/Land-Cover Types, Lower CFRB 2006.

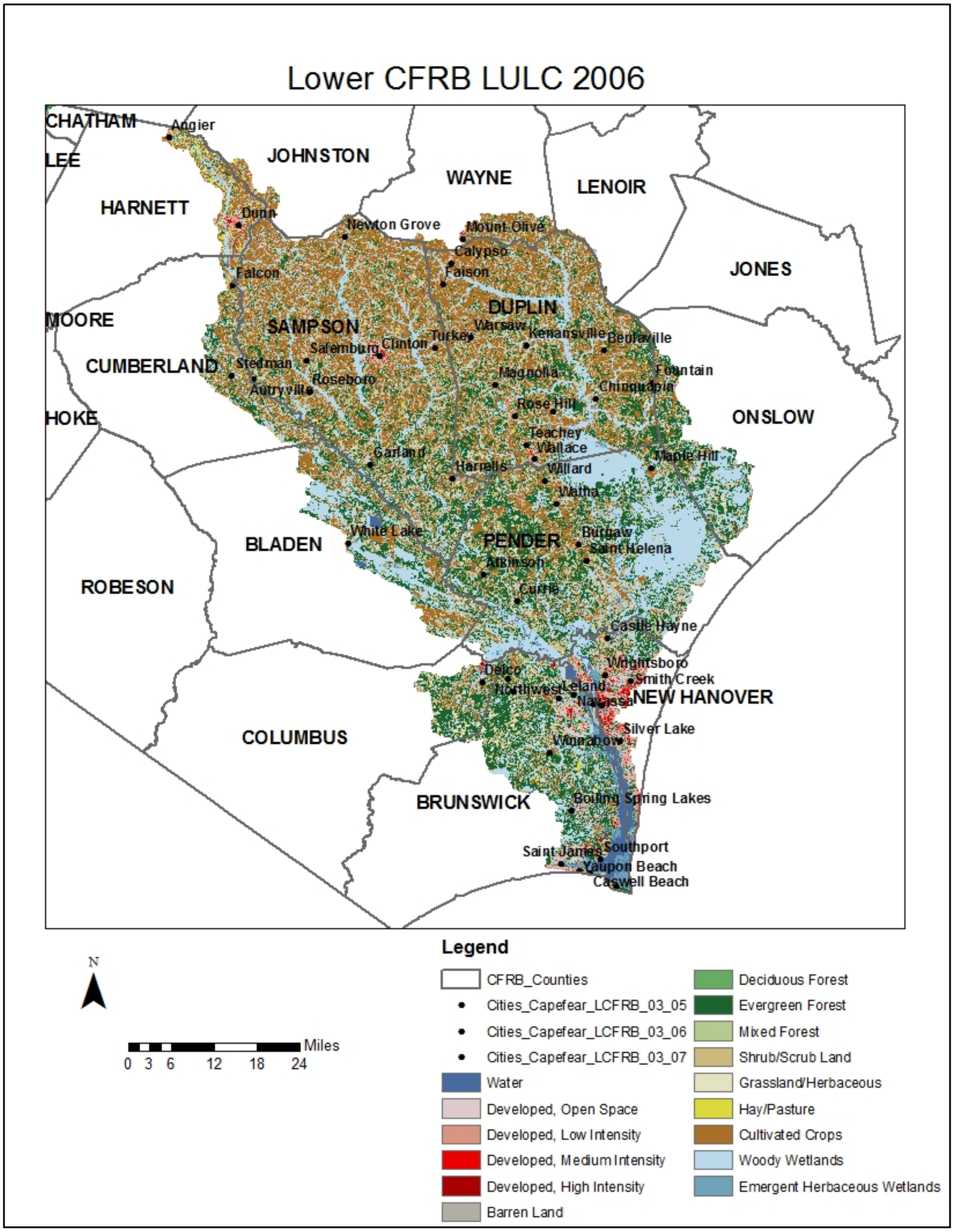

Figure 31. Land-Use/Land-Cover Types Across the Lower CFRB, 2006.

LCFRB: Fecal Coliform

In both 2001 (i.e. October 2000 to October 2001) and 2006 (i.e. October 2006 to October 2007), fecal coliform displayed the greatest variability among the dependent variables for stations included in this study (Tables 9 and 10). Fecal coliform samples ranged from a high of 261 col/100ml to a low of 29 col/100ml with an annual average of 89 col/100ml in 2001. Unlike the other physiographic regions, none of the LCFRB station annual averages exceeded the state guideline for fecal in 2001. In 2006, fecal concentrations ranged from a high of 1,448 col/100ml to a low of 41 col/100ml with an annual mean of 271 col/100ml. As with previous observations of fecal coliform trends at both the entire river basin and physiographic region scales, fecal coliform samples are highly variable from the mean. The largest increase in fecal coliform the LCFRB occurred at station BC117, which represents a station draining an individual watershed In Pender County, which includes the City of Burgaw. Fecal coliform counts at station BC117 increased by 1,233 col/100ml with notable monthly increases occurring during the summer months (Figure 32). Review reports from the Center of Marine Science (CMS) at the University of North Carolina at Wilmington and personal communication with both researchers at CMS and NC DENR revealed that the City of Burgaw's WWTP had chronic issues with excessive spills and leaks that resulted in spikes in fecal at station BC117. NC DENR SSO incident reports noted that from 2006 to 2007 this WWTP spilled 2,600 gallons of raw sewage with 1,205 gallons reaching nearby surface waters.

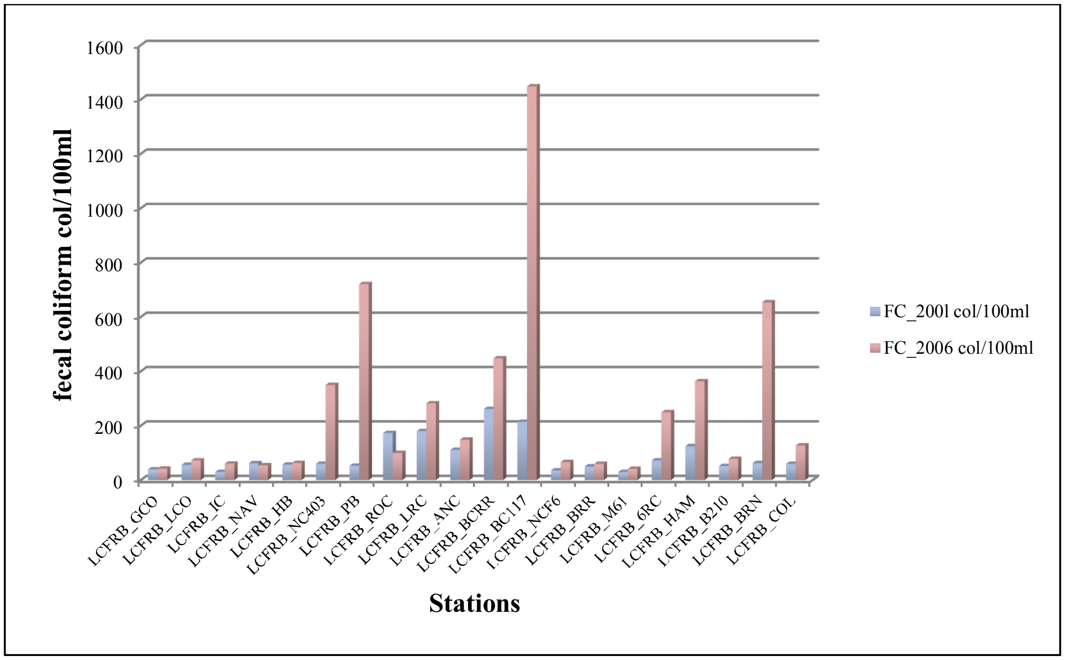

Figure 32. Changes Fecal Coliform from October 2000 to 2001 to October 2006 to October 2007 for Water Quality Monitoring Stations Included in this Study Located in the Lower CFRB.

When considering the landscape that characterized this watershed in 2001, cultivated cropland accounted for the largest land type (34% km2), with evergreen forest (21% km2), and shrub/scrub (17% km2) land accounting for the second and third largest land types. Development represented 16 percent of the landscape, while agricultural land represented 36 percent (Figure 32). According to the NC DENR animal operation permit database, there were no animal feeding operating in this watershed, however, operations that are not permitted by the state may be present. Analysis of the precipitation patterns indicated that the total precipitation increased from 38 inches in 2001 to 43 inches in 2006. In 2006, dominant land types in the watershed largely mimicked that of 2001. Changes in the landscape included a 0.35 percent increase in development and wetlands, a 5.6 percent increase in forestland, and a 0.26 percent decrease in agricultural land. As noted with pervious landscape trends, this watershed did not experience significant changes in land types from 2001 to 2006 leading one to conclude that human activities or features associated with the landscape (e.g. stormwater infrastructure) may have caused significant increases in fecal concentrations within this watershed (Figures 33 and 34). The increase in percent forestland may be attributed to forestry/silviculture practices that are common in this region. As previously noted, forestland may attract wildlife and recreational activities that have been associated with increases in fecal concentrations (Line et al., 2008). Additionally, the City of Burgaw is located in this watershed and has experienced increases in development that could be related to an increase in population from 2001 to 2006 (US Census Bureau, 2010). Increases in human population have been associated with increases in the number of wastewater treatment plants as well as increases in domestic pet waste (Rothenberger et al., 2009; Mallin et al., 2009). Although there was not an increase in the number of WWTPs in this watershed, individuals living outside the city limit may use septic systems that have been associated by Cahoon et al. (2006) to increases in fecal concentrations in nearby surface water systems in neighboring counties. Although there were minute changes in the landscape from 2001 to 2006, development in the watershed was largely associated with exurban development and low intensity development. As previously noted, these land types including recreational and residential areas that have been associated with increases in fecal concentrations in local and regional surface water systems. Several studies in the LCFRB (Mallin et al., 2000; Mallin et al., 2001) have related both increase in human populations and spatially dispersed development patterns with increases in fecal concentrations.

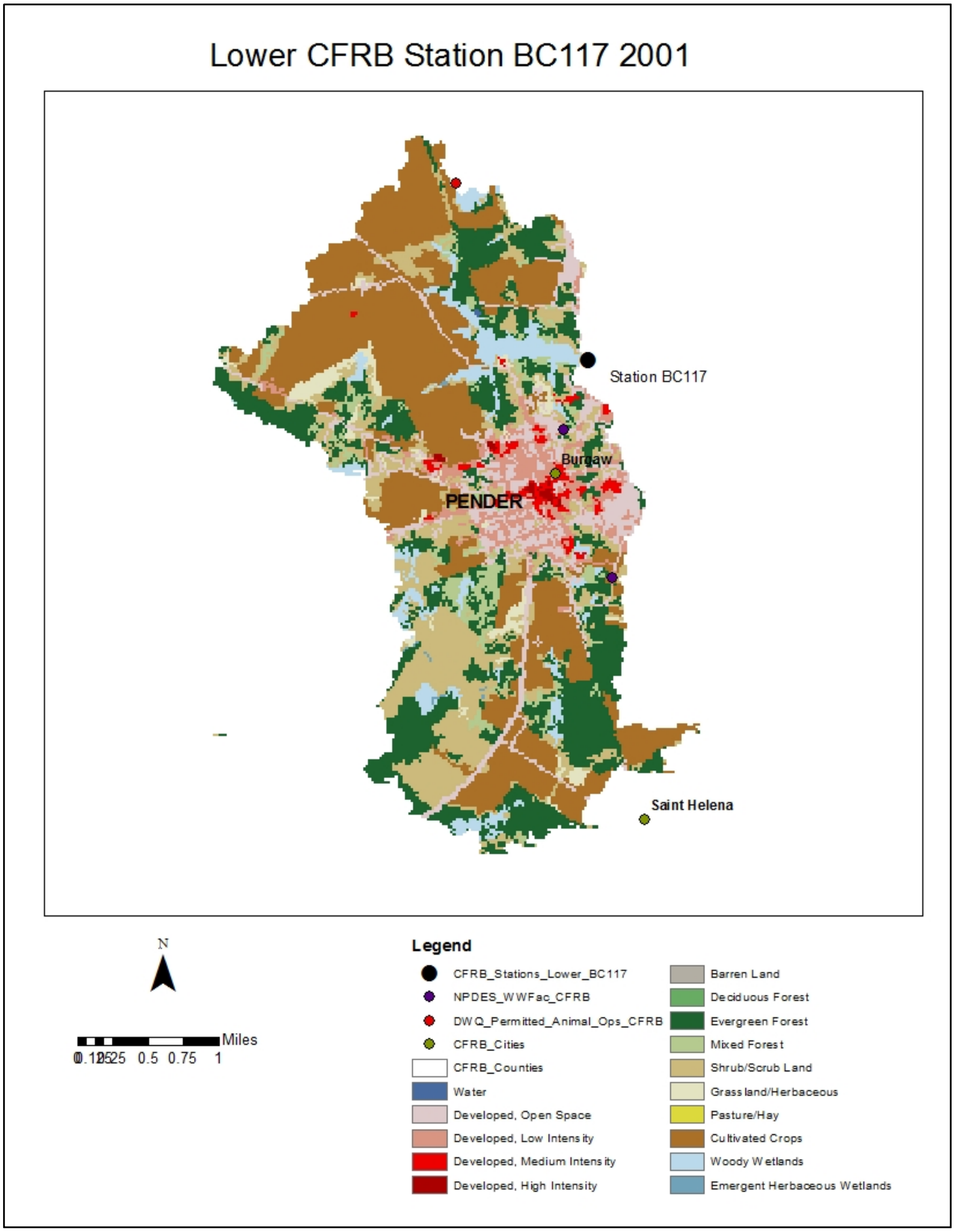

Figure 33. Land-Use/Land-Cover Types Draining to LCFRB Station BC117, 2001.

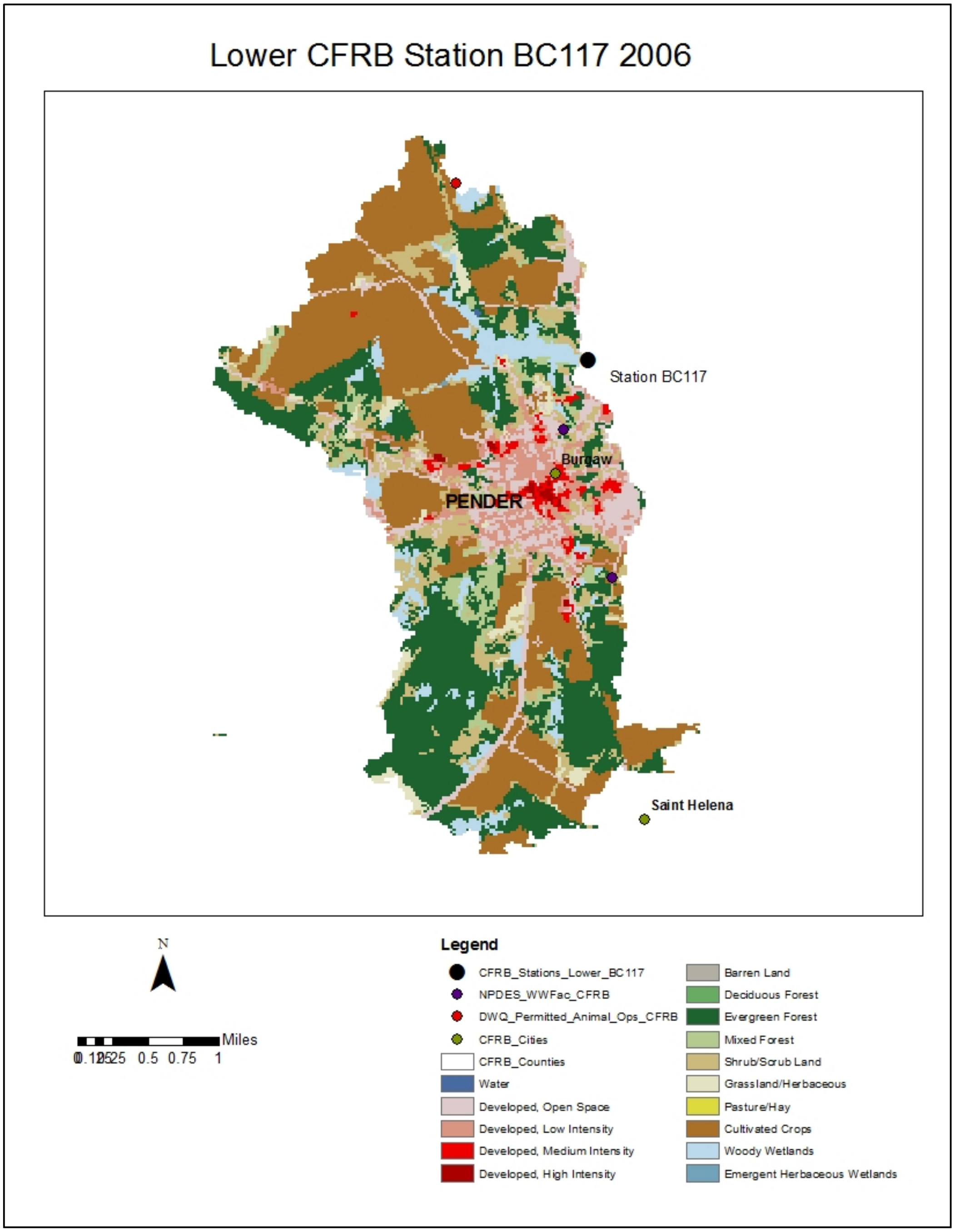

Figure 34. Land-Use/Land-Cover Types Draining to LCFRB Station BC117, 2006.

Water Quality and Land-Use/Land-Cover Trends from 2001 to 2006

When considering the geography of water quality at multiple geographical scales across the CFRB from October 2000 to 2001 (i.e. 2001) to October 2006 to October 2007 (i.e. 2006), Fecal coliform tends to be a significant parameter at both the river basin and physiographic region scales. At the river basin scale, 26 percent of station annual averages exceeded the NC DENR guideline for fecal coliform in 2001. These station were only located in the Upper and Middle CFRB with a majority of the stations being located in the UCFRB in both urban and agricultural watersheds. The percent of stations in this study exceeding the NC DENR guideline for fecal increased to 32 percent in 2006. As demonstrated and spatially illustrated in the previous sections, these stations are not only located across all of the physiographic regions, but also in watersheds dominated by agriculture, urban, and forest land as well as watersheds characterized by mixed landscape patterns. Only seven of the stations throughout the basin exceeded the NC DENR guideline for fecal coliform in both 2001 (i.e. October 2000 to October 2001) and 2006 (i.e. October 2006 to October 2007). Additionally, fecal coliform counts decreased in the UCFRB, while fecal counts increased in the LCFRB during the study period. Although this study considered the annual averages of each station by parameter, it has been noted that a majority of the significant increases in fecal have been linked to WWTP spills and infrastructure leaks. These events may mask true relationships between land types and fecal across the river basin during this time period. When considering the spatial distribution of station annual averages that exceeded the state NO2-NO3 guideline for drinking water by stream classification type, only one station exceeded the NO3-NO2 guideline in 2006 (UCFRB 06). Although none of the stations annual averages fell below the state DO guideline for both years, monthly samples indicate that several stations continuously fell below the state guideline from June to September. Applying the EPA point source recommendations for P and NH3-N to station annual averages analysis of the descriptive statistics illustrated that none of the stations exceeded the recommendation for NH3-N. In contrast, two different stations (UCFRB station 39 and LCFRB BC117) exceeded the recommendation for P in 2001 and LCFRB station BC117 exceeded this recommendation for both years. Since the data selection process employed in this study resulted in several stations located within watershed characterized by large concentrations of CAFOs, particularly in the LCFRB, being excluded it is beyond the scope of this analysis to determine how and to what extend nutrients and fecal impact these watersheds. As previously noted, several studies have concluded that CAFO activities in the LCFRB have and continue to impact surface waters in this region.

In both 2001 (i.e. October 2000 to October 2001) and 2006 (i.e. October 2006 and October 2007) agricultural and forested land largely characterized the river basin's landscape, however, development appears to be increasing in and around the urban core. From 2001 to 2006, there was a 0.14 percent increase in development, largely driven by exurban and low intensity development, and a 0.06 percent increase in agricultural land across the basin. At the physiographic scale, the largest increase in development occurred in the MCFRB, while the largest increase in agricultural land occurred in the LCFRB (Figure 10). Although it is not likely that small changes in land types contributed significantly to the increase in fecal concentrations, there appeared to be landscape transitions taking place across the basin of forestland and wetlands being converted to urban and agricultural land. Furthermore, it may be the case that current landscape patterns and human activities and features on the landscape may contribute significantly to poor surface water quality when compared to changes in the landscape alone.

Although the literature has linked several land types including urban, agriculture, and disturbed forest to increases in fecal coliform, by observing the descriptive statistics for fecal and assessing landscape changes, it does not appear that land types alone accounted for the significant changes in fecal. To account for these, one might consider that events such as WWTP and septic system leaks and spills, activities including the clear cutting of forest and the spraying of livestock manure on the landscape may contribute to the drastic annual averages of fecal that were driven by extreme monthly increases in fecal concentrations. In addition, increases in human populations may not only lead to the overcapacity of sewer infrastructure, but they may also contribute to increases in the population of domesticated pets whose waste may runoff into local surface water systems. Applying regression analysis in the forthcoming section will assist in determining the statistical significance of relationships between the water quality parameters under investigation and LULC types, differences between the physiographic regions, the potential influence of precipitation patterns, and the presence and amount of livestock located in animal feeding operations throughout the river basin. This analysis will assist in not only identifying statistically significant relationships between the dependent and independent variables under investigation, but it will also serve as a baseline for future research related to water quality trends across the CFRB. This assessment is necessary in identifying not only what may be influencing the impairment of surface water, but also the spatial context of this impairment across the river basin. Taking a spatial approach to understanding surface water quality trends throughout the basin may assist in protecting surface water resources for the basin's growing human population as well as wildlife habitat.

Regression Analysis

The primary purpose of this dissertation is to conduct one of the first studies that spatially illustrates and statistically explains relationships between water quality and land types across the entire Cape Fear River Basin from October 2000 to October 2001 (i.e. 2001) and October 2006 to October 2007 (i.e. 2006). Regression analysis is commonly used to determine the best mathematical expression that describes the functional relationships between one response (dependent) and one or more independent (predictor) variables. In this study, regression analysis was conducted for 2001 and 2006 in an effort to develop the primary solution that can help explain these relationships across a large geographical scale for each of the water quality parameters under investigation. Regression analysis was selected because it applies an automated algorithm that adds and subtracts variables to determine which variables most significantly enhance the final regression models. The results of the regression process included providing two primary statistical components, the R-squared value and the b coefficient. R-squared is useful because it is reported as a measure of how successful the regression model was in explaining the response variable and has values between 0 and 1. The closer R-squared is to 1 the better the regression model is at explaining the relationship between the explanatory and response variables. Given that the water quality data can be highly variable, each of the stations' annual averages for each parameter were transformed using a natural log transformation prior to regression analysis.

Regression Interpretation

Prior to running the regression models, station annual averages for each of the water quality parameters was transformed using a natural log. This process is common when assessing water quality data because this type of data can be highly variable depending on climatic, topographical, seasonal, and ecological conditions or if human activities have contributed to increases in water quality parameter concentrations. When interpreting the coefficients of regression models, the coefficients will represent a percent change that is predicted to occur between a given relationship between the dependent and independent variables.

Fecal Coliform from October 2000 to October 2001

Analysis of the descriptive statistics for each of the water quality variables indicated that fecal coliform concentrations have a significant impact on surface water quality across the Cape Fear River Basin. The summary of the results of the stepwise regression analysis for fecal coliform in 2001 revealed that four independent (predictor) variables were key factors in shaping the spatial distribution of fecal coliform across the river basin from October 2000 to October 2001 (i.e. 2001). The R-squared value of the model was 0.48 (Table 11), suggesting that 48 percent of the variation in fecal coliform can be explained by the predictor variables UCFRB region, exurban development (i.e. DOS), percent mixed forest land, and total precipitation. The F-score, which measures the overall accuracy of the equation, was 15 with a p-value of 0.00, indicating that the regression analysis is significant at the 5 percent confidence interval level.

Table 11. Model Summary of Fecal Coliform Across the Cape Fear River Basin from October 2000 to October 2001.

Model	**Independent Variables**	**Model r^2**	**Unstandardized b Coefficient**	**Exponent Value**	**Percent Change**
1	Constant	0.35	4.54		
	UCFRB Region		1.47	4.39	339%
2	Constant	0.40	4.29		
	UCFRB Region		1.14	3.12	212%
	% Exurban Development		0.03	1.03	3%
3	Constant	0.43	3.79		
	UCFRB Region		1.18	3.25	225%
	% Exurban Development		0.04	1.04	4%
	% Mixed Forest		0.12	1.12	12%
4	Constant	0.48	6.56		
	UCFRB Region		0.74	2.10	110%
	% Exurban Development		0.05	1.05	5%
	% Mixed Forest		0.16	1.18	18%
	Total Precipitation 2001		-0.07	0.93	-7%
	All p-values <0.05				

The final regression model for fecal coliform from October 2000 to October 2001 can be formally expressed as follows:

Log FC (2001) = 6.56 + 0.74 **UCFRB** + 0.05 **DOS** + 0.16 **MF** – 0.07 **PT**

Where,

FC = Fecal coliform col per 100ml

UCFRB = Upper Cape Fear River Basin

DOS = Percent Exurban Development

MF = Percent Mixed Forest

PT = Precipitation, Total

Upper Cape Fear River Basin (UCFRB)

The first variable to enter the regression model was the Upper Cape Fear River Basin (UCFRB) region. The empirical results from this regression analysis found that the UCFRB region was a key predictor in explaining the spatial variability in fecal coliform concentrations across the river basin in 2001 (i.e. October 2000 to October 2001). The relationship between the UCFRB region and fecal coliform concentrations across the basin in 2001 was positive indicating that compared to the other physiographic regions, fecal coliform concentrations at stations located in the UCFRB were 110 percent higher. The UCFRB region represents the most highly urbanized region in the CFRB with development largely concentrated in and around the cities of Greensboro, High Point, Jamestown, Burlington, Durham, and Chapel Hill. In addition to these concentrated development patterns, this region comprised 27 percent agricultural and 47 percent forest LULC types indicating that there are diverse landscape patterns on the fringe of development. Furthermore, the UCFRB contains the headwaters of the Deep and Haw Rivers that merge downstream to form the main stem of the Cape Fear River. As a result, land types and activities that increase fecal concentrations in surface waters located in the UCFRB may contribute to increases in fecal concentrations downstream illustrating both a local and regional impact to surface water systems.

From October 2000 to October 2001 (i.e. 2001), the UCFRB was identified as the physiographic region that comprised the highest number of monitoring stations across the river basin with annual averages that exceeded the state guideline for fecal coliform. As noted in the descriptive statistics section, this region experienced several spikes in fecal concentrations in 2001 that were largely associated with wastewater treatment plant (WWTP) spills and related infrastructure leaks. Given this finding, activities on the landscape (e.g. agricultural practices, construction activities, etc.) and the spatial configuration of landscape patterns in this region may help to explain the significance of monitoring stations in the UCFRB region that were included in this study when considering the geography of fecal concentrations across the CFRB. Spikes in fecal concentrations were found at stations located in watersheds characterized by urban, agricultural, and forested landscapes. This may be due to the fact that although WWTPs are typically located within and in close proximity to developed areas, the piping systems that support this function may traverse a variety of land types. Additional sources of high fecal concentrations in agricultural and forested watershed may also include failing septic systems, livestock manure, and waste associated with CAFO activities and wildlife excreta. For example, figure 35 illustrates how in Duplin County, located in the LCFRB, fecal from CAFOs can be spread onto the landscape. This figure illustrates not only the common practice of spraying manure onto fields, but also how this material can pool on the surface leading to surface water pollution from both surface runoff and groundwater processes.

Figure 35. CAFO Spraying Activities on a Field Located in Duplin County, NC in the LCFRB. Source: Mallin, 2013

As cities in the UCFRB region continue to expand beyond the urban core, leaks and spills from failing WWTP infrastructure and septic systems may impact watersheds that are characterized by development as well as watershed on the fringe of development that are primarily characterized by agricultural and forest land. Understanding the spatial extent of these systems and where spills and leaks occur may further illustrate the spatial distribution of fecal concentrations within physiographic regions as well as across the entire river basin.

Percent Exurban Development

The second variable to enter the regression model was percent exurban development (i.e. Developed, Open Space (DOS)). The b coefficient suggests a positive relationship existed between this variable and fecal coliform concentrations. Specifically, the model predicted that if the percent of exurban development increased by one percentage point, fecal coliform concentrations would increase by 5 percent, holding all other predictor variables constant. This land type is characterized by areas primarily consisting of lawn grasses (e.g. large-lot single-family homes, parks, golf courses, recreational areas, and landscaped areas) and impervious surfaces that account for less than 20 percent of the total landscape. This may also include a mixture of constructed features that may represent landscape gradients from forested or rural land to dispersed suburban development. From October 2000 to October 2001, exurban development accounted for 3.20 percent of the total river basin and 8.7 percent of the UCFRB, 6.4 percent of the MCFRB, and 3.8 percent of the LCFRB physiographic regions. Despite representing a small percentage of the land types present across the CFRB, this land type appears to play a significant role in the increase of fecal concentrations to surface waters throughout the river basin.

The literature has suggested that transitional landscapes, including less developed areas surrounding the urban core, may experience changes in stream water quality as a direct result of human disturbances to the landscape. Several studies have noted adverse impacts to stream quality in watersheds with impervious surfaces as low as 5 to 20 percent (Schoonover et al., 2005; Booth & Jackson, 1997; Mallin et al., 2001; Walsh et al., 2005; Schueler, 1994 and others). In the LCFRB, Mallin et al. (2001) observed that watersheds with less than 10 percent impervious surfaces exhibited good water quality, while watersheds with impervious coverage between 10 to 20 percent were often impaired. Transitional landscapes, such as exurban development, may have different landscape configurations and transitional patterns such as urban to suburban, rural to suburban, and forest to rural and or suburban land. The literature suggests that during landscape transitions, especially forestland or rural land to suburban, the percentage of impervious surface can increase. This is typically in the form of residential and commercial development as well as an increase in spatially dispersed road networks. During this transition, new sources of fecal concentrations may come from the increase in domestic pets associated with increasing human populations as well as the presence, expansion or establishment of spatially dispersed WWTPs and related piping systems (Rothenberger et al. 2009). In addition, non-point sources of fecal may derive from the establishment of varying stormwater infrastructural designs, such as curb and gutter street systems, which quickly convey high concentrations of pollutants to surface waters during storm events (Mallin et al., 2001).

The inclusion of this predictor variable and the exclusion of the remaining developed LULC types in this model signifies that among the developed land types, exurban development is the most influential LULC type when considering the spatial distribution of fecal concentrations across the basin in 2001 (i.e. October 2000 to October 2001). The findings in this analysis support the initial hypothesis that less urbanized areas will often exhibit poorer water quality when compared to high intensity development. In this case, increases in exurban development will contribute to increase in fecal concentrations in surface water systems throughout the river basin. This is a noteworthy finding because it has been well documented that the human population of the CFRB is not only increasing, but less dense development patterns are the primary landscape forms associated with this increasing population. Identifying and understanding relationships that exist between different landscape features found within suburban development may assist local and regional planners and environmental resource agencies with more closely monitoring transitional landscape in an effort to develop more comprehensive regulations aimed at protecting surface water quality.

Percent Mixed Forest

Percent mixed forest was the third variable to enter the regression analysis. The relationship between it and fecal concentrations was positive suggesting that as the percent mixed forest increased by one percentage point, fecal coliform concentrations increased by 18 percent holding all other predictor variables fixed. Mixed forest land are defined as areas dominated by trees generally greater than 5m tall, which cover more than 20 percent of the landscape. Additionally, neither deciduous nor evergreen species are greater than 75 percent of the total tree cover. Unlike undisturbed forest in which no human activities or land disturbances have taken place, mixed forest may include disturbed land activities including silviculture practices, rural development, gamelands, and dispersed road networks. Across the river basin, this land type was typically identified in close proximity to exurban development possibly indicating that this may be a transitional landscape type that may become more developed overtime. In 2001, mixed forest only accounted for 2.12 percent of land types across the river basin. Although this is a small percentage when compared to other land types, the model suggests that even a small percentage increase of this land type can contribute to increases in fecal coliform concentrations in surface water systems throughout the basin. When assessing which physiographic region contains the largest percentage of mixed forest land, one will note that this primarily occurs in watersheds located in the UCFRB and MCFRB.

Typically, watersheds with a high percentage of undisturbed forest land tend to support surface water systems with fewer concentrations of pollution when compared to urban and agricultural watersheds. However, Megahan and King (1985) noted that erosional processes tend to be greater in forested areas than on most types of agricultural land primarily due to steeper slopes and more shallow soils. When considering specific activities and characteristics associated with forested watersheds and increases in fecal coliform concentrations, Line et al. (2008) observed that roadways (unimproved) that were utilized by hunters, horseback riders, and trappers and traversed crossed creeks and river systems contributed to increases in fecal concentrations. Additionally, disturbed forest may include ditch systems that are typically installed to drain water in the soil profile for forest management practices were also found to be associated with increases in fecal coliform. Ensign and Mallin (2001) observed changes in stream water quality following a 130-acre clear-cut timber harvest in the Goshen Swamp located in the LCFRB. Although forest was the dominant land-cover, increases in fecal coliform were associated with clear-cutting practices even 15 month after the timber harvest when vegetation was being re-established.

Prior to this regression analysis, it was anticipated that watersheds largely characterized by urban development would contribute to poorer surface water quality when compared to watersheds characterized by forested landscapes. A second assumption was that watersheds that were transitioning from forestland to development would exhibit poorer water quality than those transitioning from agriculture to urban development. The findings in the 2001 (i.e. October 2000 to October 2001) regression analysis for fecal suggested that a one percent increase in mixed forest land resulted in an 18 percent increase in fecal concentrations across the basin. In contrast, a one percent increase in exurban development resulted in a 5 percent increase in fecal concentrations. This may be due to the fact that mixed forest may represent a transitional landscape that is transitioning from a natural state to one that is increasingly disturbed by human activities and development. In contrast, areas characterized by exurban development may have already experienced an abrupt transition from natural to development and the landscape may be becoming more concentrated with developed landscape patterns. This finding contributes significantly to the literature because a majority of the literature suggests that although fecal coliform concentrations may be higher in urban and agricultural watersheds, disturbed forested landscapes may contribute smaller amount of fecal coliform to surface water systems. This analysis illustrates that percent mixed forest contributes higher concentrations of fecal when compared to percent exurban development, suggesting that as forest land is developed it may contribute to higher concentrations of fecal in some surface waters systems. Applying higher resolution imagery may verify in more detail what activities are taking place on the ground. Since exurban development and mixed forest land both contribute to increases in fecal concentrations and are typically spatially located in close proximity to one another, it will becoming increasingly important to understand how these transitional landscapes impact surface waters across the CFRB in more detail.

Total Precipitation

The fourth and final variable to enter the regression analysis was total precipitation. The b coefficient illustrates an inverse relationship suggesting that as total precipitation increases by one inch fecal concentrations will decrease by seven percent across the river basin. The literature has mixed results when considering relationships between precipitation, typically in the form of rainfall, and fecal concentrations. In some cases, fecal concentrations can be diluted by an increase in rainfall (Potter et al. 2004) and in other cases, especially in areas with stormwater systems or septic tanks, fecal concentrations can increase rapidly in river and stream systems even after a short duration of rainfall. In contrast, Cahoon et al. (2006) observed increase in fecal concentrations in periods of no rain indicating that poorly designed and or located septic system may contribute to impaired water quality. The duration of rainfall as well as the duration of time that passes prior to a sample being collected are all important factors when considering the spatial relationships between rainfall and fecal concentrations in surface water systems. In the rural watersheds located in the Coastal Plains region of the CFRB, Mallin et al. (2001) observed a strong correlation of fecal counts and turbidity with rainfall in the previous 24 hours in watersheds containing extensive industrial swine and poultry operations, as well as within watershed with more traditional agricultural practices. Hill et al. (2006) suggested that even average rainfall events have resulted in the bursting and overflowing of manure lagoons from CAFOs, stormwater overflows, runoff from pastures and range lands as well as sewage pipes that may become clogged with litter and debris during storm events. Chigbu et al. (2005) note that the amount of salinity in the water has an inverse relationship with fecal suggesting that fecal coliform bacteria may not survive in surface waters with higher salinity. This is important to note in the CFRB since surface waters in the lower portions of the LCFRB region may be influenced by tidal patterns and salt water intrusion.

Although this model suggests that as rainfall increases by one inch, fecal concentrations will likely decrease by 7 percent, it is difficult to determine the true relationship of this variable since stream flow data are not available at monitoring station locations. It should be noted that a majority of the CFRB landscape is represented by forest and agricultural land that largely lack extensive stormwater systems that quickly convey non-point sources of pollution to nearby surface water systems. It should also be noted again that many of the monitoring stations located near high concentrations of CAFOs, especially in the LCFRB, were omitted from this analysis due to data quality issues (i.e. inadequate water quality data and issues with GIS delineation of watersheds). High natural infiltration processes and the absence of several monitoring stations located in watersheds with high concentrations of CAFOs may help to explain why an increase in precipitation will result in decreased in fecal concentration levels.

Fecal Coliform from October 2006 to October 2007

Like the regression model for October 2000 to 2001 (i.e. 2001), concentrations of fecal coliform were one of the most significant water quality parameters shaping the geography of water quality across the river basin from October 2006 to October 2007 (i.e. 2006). The summary of the results of the regression analysis for fecal coliform in 2006 reveal that four predictor variables are key factors in shaping the spatial distribution of fecal coliform concentrations across the river basin in 2006. The R-squared value of the model is 0.31 (Table 12), suggesting that 31 percent of the spatial variation in fecal coliform concentrations can be explained by percent mixed forestland, percent exurban development, percent scrub/shrub land, and the UCFRB region. The F-score is 7.42 with a p-value of 0.00 indicating that the regression analysis is significant at the 5 percent confidence level.

Table 12. Model Summary of Fecal Coliform Across the Cape Fear River Basin from October 2006 to October 2007.

Model	Independent Variables	Model r^2	p-value	Unstandardized b Coefficient	Exponent Value	Percent Change
1	Constant	0.09	0.00	4.45		
	MCFRB Region		0.01	-0.48	0.61	-39%
2	Constant	0.16	0.00	4.17		
	MCFRB Region		0.00	-0.61	0.54	-46%
	% Mixed Forest		0.01	0.10	1.10	10%
3	Constant	0.21	0.00	3.83		
	MCFRB Region		0.00	-1.52	0.59	-41%
	% Mixed Forest		0.00	0.13	1.13	13%
	% Exurban Development		0.03	0.02	1.02	2%
4	Constant	0.27	0.00	3.48		
	MCFRB Region		0.01	-0.46	0.63	-37%
	% Mixed Forest		0.00	0.13	1.13	13%
	% Exurban Development		0.00	0.03	1.03	3%
	% Scrub/Shrub Land		0.03	0.03	1.03	3%
5	Constant	0.31	0.00	2.98		
	MCFRB Region		0.64	-0.11	0.84	-16%
	% Mixed Forest		0.00	0.13	1.13	13%
	% Exurban Development		0.00	0.03	1.03	3%
	% Scrub/Shrub Land		0.00	0.07	1.07	7%
	UCFRB Region		0.04	0.58	1.78	78%
6	Constant	0.31	0.00	2.87		
	% Mixed Forest		0.00	0.13	1.14	14%
	% Exurban Development		0.00	0.03	1.03	3%
	% Scrub/Shrub Land		0.00	0.07	1.08	8%
	UCFRB Region		0.00	0.67	1.96	96%

The final regression model for fecal coliform from October 2006 to October 2007 can be formally expressed as follows:

Log FC (2006) = 2.87 + 0.13 **MF** + 0.03 **DOS** + 0.07 **SS** + 0.67 **UCFRB**

Where,

FC = Fecal coliform col per 100ml

MF = Percent Mixed Forest

DOS = Percent Exurban Development

SS= Percent Shrub/Scrub Land

UCFRB = Upper Cape Fear River Basin Region

Percent Mixed Forest

Percent mixed forest was the first predictor variable to enter into the regression model and as a result, it represented the most significant variable when considering the spatial distribution of fecal concentrations across the basin in 2006. The b coefficient predicts that as the percent mixed forest land increases by one percentage point, fecal coliform concentrations across the basin will increase by 14 percent. This is a slightly lower percent increase in fecal concentrations when compared to the influence of percent mixed forest in the 2001 fecal coliform model (18% increase). As previously noted, this landscape is characterized by areas dominated by trees and may include disturbed land activities including silviculture practices and rural development. Although forestland slightly decreased across the basin from 2001 to 2006 (0.33%), this decrease was primarily found around already developed areas where forestland was transitioning into exurban and low intensity development or agricultural land.

The literature suggests that fecal may come from both natural and anthropocentric sources in forested areas including wildlife and domestic pet waste, failing septic systems, and overflow and leaks from sewer systems that may traverse the landscape. In addition, human activities on the landscape may create conditions conducive for fecal to be conveyed to nearby surface water systems. The landscape trends across the basin suggests that this LULC type is decreasing with more development primarily occupying land areas previously occupied by mixed forestland. Developed areas are typically characterized by increases in impervious surfaces that have been well documented to increase fecal concentrations in surface waters. As the landscape continues to transition from a natural landscape to one characterized by human activities and development it will become increasingly important to develop policies that account for these transitions by considering, not only the land type itself, but the spatial relationships between these new features on the landscape and fecal concentrations in surface water systems.

Percent Exurban Development

Percent exurban development (i.e. Developed Open Space (DOS)) was the second variable to enter the regression model where a one percent increase in exurban development resulted in a three percent increase in fecal concentrations in the CFRB. Although this is a relatively small percentage increase in fecal, the nature of this transitional land type may indicate that over time the landscape is becoming more developed, which is likely influenced by the increasing human population across the river basin. This LULC type includes less than 20 percent impervious surfaces, large lot residential homes, recreational areas, and a mixture of constructed materials. Suburban development can typically be found encircling urbanized areas and often serves as a transitional area between urban development and forest or agricultural land. Tong et al. (2009) suggested that as the landscape transitions, the types of ground cover, evapotranspiration, infiltration, erosional processes and sediments will change impacting both the total quantities of pollutant loads as well as the transport pathways that convey pollutants to surface water systems. Additional changes may include increases in human populations that are often associated with increases in impervious surfaces associated with buildings and related driveways and parking lots, road networks, domestic pets, and infrastructure including WWTPs all of which have been noted to increase fecal concentrations in surface water systems (Rothenberger et al., 2009; Mallin et al., 2001; Ahearn et al., 2005 and others). Holland et al. (2004) notes that although human populations may increase, these population may be spatially dispersed due to the large residential lot sizes and the highly dispersed road networks that connect residential, commercial and industrial land types.

From October 2000 to 2001 (i.e. 2001) to October 2006 to October 2007 (i.e. 2006) developed areas represented the largest increase and forest and wetlands represented the most significant decrease in land types across the CFRB. Exurban development typically occurred on the periphery of areas that were already developed including the cities of Greensboro, High Point, Burlington, Durham, Chapel Hill, Fayetteville, and Wilmington. It is anticipated that as the population of the CFRB continues to grow, areas that are characterized by exurban development may transition into low and medium intensity development. This transition may include an increase in commercial and residential development as well as schools and public services that support these populations. As a result, the spatial extent of stormwater systems and impervious surface will increase making it more likely that non-point sources of pollution, including fecal, will enter stream and river systems untreated. It was previously suggested that forest land, such as mixed forest, would contribute less fecal concentrations when compared to lower intensity forms of development. However, like the 2001 regression model for fecal, this model also suggests that mixed forest, not exurban development, contributes a higher percentage of fecal concentrations to surface water systems in the CFRB. This may be due to the varying landscape activities taking place on mixed forest landscape including, but not limited to, hunting and horseback riding in addition to human development, which collectively, may increase fecal concentrations to nearby surface waters.

Percent Shrub/Scrub Land

Percent shrub/scrub land is the third variable to enter the regression model where the b coefficient suggests a positive relationship exists indicating that a one percentage point increase in shrub/scrub land will increase fecal concentrations across the basin by seven percent holding all other predictor variables constant. This LULC type is defined as areas dominated by shrubs that are less than 5 meters tall with a shrub canopy that is typically greater than 20 percent of the total vegetation. In addition, mixed forest may include true shrubs, young early trees or trees stunted from environmental conditions. In relation to the North Carolina landscape, the North Carolina Wildlife Resources Commission (WRC) notes that this land type is typically located in the Coastal Plains region and is characterized by low woody vegetation and herbaceous plants. Shrub/scrub land in this region is typically created by disturbances including clearcutting, disking, or burning and are often found at the transition between agricultural lands and forestland and is frequently found in the understory of open pine stands (WRC 2014). When observing the percentage of shrub/scrub land across each of the physiographic regions in the CFRB in 2006, this shrub/scrub land represented approximately two percent of the UCFRB, eight percent of the MCFRB, and 12 percent of the LCFRB.

Silviculture practices that may include clearcutting and burning are prevalent throughout the CFRB, especially in the MCFRB and LCFRB. These practices often result in accelerated soil erosion that may carry non-point sources of pollution, including fecal, to nearby surface waters (Kasprak et al. 2013). As previously discussed, Ensign and Mallin (2001) noted increases in fecal concentrations downstream from clearcutting activities even in the presence of a natural vegetative buffer. Other practices may include the burning of forestland to quickly clear land for agricultural use or on agricultural lands to convert the land to an alternative agricultural practice. This process leaves soils unstable and exposes them to erosional processes, especially where slopes are present. As a result, fecal from livestock and or wildlife waste may attach to sediments that, once eroded, may enter stream systems through runoff processes. Along transitional landscapes, such as shrub/scrub land, Sebestyen and Verry (2011) observed an increase in fecal following the establishment of cattle grazing in a watershed that was largely converted from forestland to agricultural pasture lands. They noted that although fecal concentrations were present prior to this landscape transition, primarily from wildlife, there were dramatic increase in fecal once grazing was established. In the Coastal Plain region of the CFRB, Mallin and Cahoon (2003) noted that livestock excrete large amounts of fecal manure that are often sprayed onto fields, even within close proximity to surface water systems and within a short period prior to rain events. This has increased the amount of fecal concentration in nearby waters as well as downstream of CAFO locations posing a risk to both ecosystem and human health. The regression model suggests that shrub/scrub land contributes a higher percentage of fecal concentrations when compared to exurban development, but contributed less fecal concentrations when compared to percent mixed forest land.

UCFRB Region

The final variable to enter the regression model for fecal coliform from October 2006 to October 2007 (i.e. 2006) was the UCFRB region. The relationship between the UCFRB region and fecal concentrations across the river basin during the study period was positive much like the 2001 (i.e. October 2000 to October 2001) regression model indicating that compared to the other physiographic regions, fecal concentrations for UCFRB monitoring stations were 96 percent higher. Although the UCFRB region is largely characterized by agricultural and forest land, it is the most urbanized physiographic region in the CFRB. As previously discussed, a majority of the monitoring stations' annual averages and monthly samples in this region exceeded the state guideline for fecal concentrations. Several of the UCFRB stations' monthly exceedances have been linked to WWTP spills (i.e. overflows and leaks). Unlike the 2001 regression model where the UCFRB region was the first variable entered into the equation, in the 2006 model, the UCFRB region was the fourth and last variable to be included. Although the number of stations whose annual averages exceeded the state guideline for fecal in this region was reduced from 2001, this region was still the primary region where excessive fecal concentrations were observed throughout the CFRB. From 2001 (i.e. October 2000 to October 2001) to 2006 (i.e. October 2006 to October 2007) both development and agricultural land increased in this region. Each of these LULC types have been linked to increases in fecal concentrations that have been previously discussed in detail. Given the large and spatially expansive amounts of WWTP activities that are associated with this region it is likely that land types alone were not solely responsible for the increases in fecal concentrations. Instead, it is more likely that the spatial extent of the infrastructure and human activities on the land that have most influenced the concentration of fecal coliform in river and stream systems within this region.

Dissolved Oxygen from October 2000 to October 2001

Another key indicator of water quality is dissolved oxygen (DO). The summary of the results of the regression analysis for DO indicate that two predictor variables, the MCFRB region and percent emergent herbaceous wetlands, are key factors in explaining 32 percent of the spatial variability of DO across the entire CFRB in 2001 (Table 13). The F-score is 16.23 and the model is significant at the 5 percent confidence level.

Table 13. Model Summary of Dissolved Oxygen Across the Cape Fear River Basin from October 2000 to October 2001.

Model	Independent Variables	Model r^2	Unstandardized b Coefficient	Exponent Value	Percent Change
1	Constant	0.24	2.03		
	MCFRB Region		0.16	1.17	17%
2	Constant	0.32	2.05		
	MCFRB Region		0.15	1.16	16%
	% Emergent Herbaceous Wetlands		-0.07	0.93	-7%
	All p- values <0.05				

The final regression model for Dissolved Oxygen from October 2000 to October 2001 can be formally expressed as follows:

Log DO (2001) = 2.05 + 0.15 **MCFRB** – 0.07 **EHW**

Where,

MCFRB = Middle Cape Fear River Basin

EHW = Percent Emergent Herbaceous Wetlands

Middle Cape Fear River Basin Region (MCFRB)

The MCFRB region was the first variable to enter the regression model for dissolved oxygen (DO) in 2001. The b coefficient suggests that among the physiographic regions, monitoring stations in the MCFRB region were 16 percent more likely to report elevated DO in their samples. In 2001, a majority of the landscape that characterized this region included 27 percent evergreen forest, 14 percent woody wetlands, 11 percent cultivated cropland, 9 percent herbaceous land, and 8 percent shrub/scrub land. Development is spatially concentrated in and around the cities of Fayetteville and Elizabethtown. Evergreen forest, which represented the largest LULC type in the MCFRB in 2001, are defined as landscapes dominated by trees generally greater than 5 meters tall, and greater than 20 percent of total vegetation cover. More than 75 percent of the tree species maintain their leaves all year and the tree canopy is never without green foliage.

Activities associated with landscapes characterized by forest and agricultural land may have varying impacts on DO in surface water systems. Binkley and Brown (1993) observed a marginal increase in DO in an undisturbed forested watershed when compared to a logged watershed, which exhibited a decrease in DO. In addition, Cookson and Schorr (2009) associated decreases in DO with increases in watershed housing density. In the Coastal Plains of the CFRB Mallin et al. (2004) observed decreases in DO related to CAFO spills which increased nutrients in nearby surface water systems. The highly dispersed forestland patterns in the MCFRB may account for this positive correlation between the MCFRB and DO. Other characteristics of the MCFRB that may contribute to increases in DO may be due to topographical changes in the stream profile, which increases the interface between the atmosphere and water column (i.e. ripples in the stream). In addition, the fact that evergreen forest characterize a majority of the MCFRB may indicate that this land type and its spatial distribution across this physiographic region may support higher concentrations of DO in surface water systems.

Percent Emergent Herbaceous Wetlands

The second and final variable to enter the regression model was emergent herbaceous wetlands (EHW). The model indicated that an inverse relationship exists between EHW and DO suggesting that as EHW increases by one percentage point, there is a 7 percent decrease in DO. Emergent herbaceous wetland types are defined as areas where perennial herbaceous vegetation accounts for greater than 80 percent of the vegetative cover and the soil substrate is periodically saturated or covered with water.

The US EPA (2014) indicates that wetlands typically have low DO because water is often stagnant in these ecosystems. McCormick and Laing (2003) observed decreases in DO in wetlands located in the Florida Everglades associated with ecological changes including increases in anaerobic metabolism and an increase in invertebrate taxa that tolerate lower DO concentrations. The researchers also note that wetland systems can be enriched with nutrients that exceed the wetlands systems ability to absorb and flush out nutrients, which may further lower DO in the water column. They observed a distinct pattern of lower DO in wetlands that experienced increases in nutrient loading, which highlighted how water quality parameters may be influencing one another in specific ecological systems. In the CFRB, increases in nutrients (eutrophication) that have resulted in the lowering of DO (hypoxic) in the river, streams and estuaries have been linked to CAFO generated pollutants (i.e. fecal and nutrients). The increase in nutrients associated with eutrophication may derive from CAFO specific activities including animal waste that are sprayed onto fields and enter stream systems through runoff and percolation into groundwater. As these nutrients move downstream they can enter wetland ecosystems that may become overloaded leading to further reductions in DO (Mallin & Cahoon, 2003). Although wetlands are naturally lower in DO when compared to other aquatic ecosystems, there is a clear need to divert excessive amounts of nutrients from these systems so that they can maintain a natural function of pollution removal, which supports both improved water quality and healthy aquatic habitats.

Dissolved Oxygen from October 2006 to October 2007

The empirical results from the regression analysis found that the spatial variability in DO concentrations in surface water systems in the CFRB was explained by a noticeably different set of predictor variables including the LCFRB region, permitted animal operation livestock headcounts (headcount), and percent emergent herbaceous wetlands (EHW). As previously noted, the MCFRB and EHW were the only variables entered into the regression model for 2001. The 2006 model explained 47 percent of the spatial variation in DO across the CFRB. The F-score was 20.27 and the regression model was significant at the 5 percent confidence level (Table 14).

Table 14. Model Summary of Dissolved Oxygen Across the Cape Fear River Basin from October 2006 to October 2007.

Model	**Independent Variables**	**Model r^2**	**Unstandardized b Coefficient**	**Exponent Value**	**Percent Change**
1	Constant	0.37	2.13		
	LCFRB Region		-0.19	0.82	-18%
2	Constant	0.43	2.56		
	LCFRB Region		-0.13	0.87	-13%
	Number of Permitted Livestock (Headcount)		-0.13	0.87	-13%
3	Constant	0.47	2.55		
	LCFRB Region		-0.09	0.91	-9%
	Number of Permitted Livestock (Headcount)		-0.12	0.88	-12%
	% Emergent Herbaceous Wetlands		-0.07	0.93	-7%
	All P values <0.05				

The final regression model for dissolved oxygen from October 2006 to October 2007 can be formally expressed as follows:

Log DO (2006) = 2.55 – 0.09 **LCFRB** – 0.12 **HC** – 0.07 **EHW**

Where,

LCFRB = Lower Cape Fear River Basin

HC = Number of Permitted Livestock (Headcount)

EHW = Percent Emergent Herbaceous Wetlands

Lower Cape Fear River Basin Region (LCFRB)

The Lower Cape Fear River Basin (LCFRB) region was the first variable to enter the regression model for DO in 2006. The b coefficient illustrates that an inverse relationship exists between monitoring stations in the LCFRB region (i.e. specifically the ones included in this study) and DO – which supports a majority of the literature regarding natural conditions, land types and activities – and DO concentrations in this region. The regression model suggested that when compared to other physiographic regions in the CFRB, monitoring stations in the LCFRB region exhibited 9 percent less DO in surface water systems located in this region. One unique attribute of this region, which includes the Coastal Plains, is the presence of a significant amount of wetlands and blackwater systems. As previously noted, under natural conditions these systems exhibit low DO that can include seasonal differences in DO where lower DO occurs in the spring and summer when compared to the fall and winter months. In addition, this region contained a high concentration of CAFOs when compared to the UCFRB and MCFRB regions.

Low DO (hypoxic conditions) in the LCFRB from natural and anthropocentric sources have been well documented. Mallin et al. (2004) noted that blackwater systems are the most abundant type of freshwater system in the Coastal Plains of the eastern United States. This system typically drains watersheds that receive a large amount of nutrient inputs from anthropocentric sources. The increase in nutrient inputs to blackwater systems may stimulate blackwater phytoplankton growth that will subsequently die and decompose becoming sources of biological oxygen demand (BOD) resulting in lower DO in streams. This region has experienced a landscape shift from traditional agricultural practices to industrial livestock production, which includes an increase in CAFOs and related activities. When considering regional differences in DO concentrations from 2001 and 2006, one will note that while the MCFRB was significant in 2001 and had a positive correlation with DO while the LCFRB was significant in 2006 and had an inverse relationship with DO in 2006. This may be due to the fact that the LCFRB contains a larger majority of wetlands and blackwater stream systems both of which are naturally low in DO. In addition, the LCFRB has the highest concentration of CAFOs activities that have been associated with lower DO in nearby surface water systems. Both natural and anthropocentric characteristics inherent within these two regions may serve as a baseline for understanding the magnitude of how both the spatial landscape patterns and natural landscape features that characterize these regions influence DO concentrations. Further analysis of detailed landscape spatial patterns, such as vegetative buffers along stream banks and the proximity of landscape features and activities to surface waters, may provide more insight into better understanding the relationships that exists between DO and these two regions of the Cape Fear River Basin.

Number of Permitted Livestock (Headcount)

The second variable to enter the regression equation for DO in 2006 was the number of permitted livestock (i.e. livestock headcounts). The b coefficient associated with this variable predicts that as the number of livestock headcount increased by one head of livestock, there would be a 12 percent reduction in DO. This association supported a majority of the literature that has linked decreases in DO with the presence of livestock, especially in CAFOs, because increases in nutrients and fecal associated with these activities have been linked to the excessive growth of algae in surface waters, which can causes hypoxic conditions. One important note about this variable that must be taken into consideration is that the number of permitted heads of livestock only represents the maximum allowed number of livestock. These permit types may be active for 5 or more years and may not accurately represent how many livestock are on the landscape or within CAFOs at any given time. Throughout the United States, especially in the CFRB, livestock production has shifted to an industrialized model that transitioned livestock (cattle, swine, and poultry) from pastures to large buildings where they are confined and fed until they are ready for market. A direct result of this change has led to the establishment of CAFOs across the landscape. As previously mentioned, activities associated with CAFOs include the establishment of waste lagoons, spraying of manure onto fields, and lagoon spills, leaks and overflows, especially during heavy rainfall and hurricanes. In the CFRB, these facilities are typically located in floodplains where manure may runoff into nearby streams or enter surface water systems through percolation into the subsurface and lateral movement through groundwater systems. Nutrients associated with cattle grazing and dairy production may also contribute to decreases in DO in nearby surface water systems. Given that a large majority of the literature on this topic has linked increases in nutrients with lower DO levels, it is possible that this activity in combination with the presence of CAFOs supports the assertion that an increase in headcounts will decrease DO levels in the surface waters of the CFRB.

Percent Emergent Herbaceous Wetlands

The last variable to enter the regression model was percent emergent herbaceous wetlands (EHW). Like the 2001 model for DO, the relationship between EHW and DO was inverse predicting that as EHW increases by one percentage point, there will be a 7 percent decrease in DO across the river basin just like in 2001. Relationships between EHW and DO have been discussed extensively in the 2001 model for DO. Although in an undisturbed state wetlands exhibit low levels of DO, excessive anthropocentric inputs (i.e. nutrients and fecal) to stream systems that feed into these wetland systems may adversely impact their effectiveness in removing nonpoint sources of pollution.

Nutrients (N02-N03, NH3-N, and P)

Beyond fecal coliform and dissolved oxygen (DO), alternative water quality metrics can include nitrate-nitrite nitrogen (NO2-NO3), ammonium nitrogen (NH3-N), and phosphorus, which are often collectively referred to as nutrients. Although the regression models associated with these metrics yielded fewer significant outcomes when compared to fecal and DO they warrant attention because they are often associated with human activities across diverse land types including urban, agricultural, and forest landscapes.

Nitrate-Nitrite Nitrogen (NO2-NO3) from October 2000 to October 2001

The UCFRB region was the first and only variable to enter the regression model for nitrate-nitrite nitrogen (NO2-NO3) in 2001. This model suggests that this region alone explains 15 percent of the variability in NO2-NO3 across the river basin in 2001. The F-score for the model is 12.73 and the model is significant at the 5 percent confidence level. The b coefficient associated with the UCFRB region predicts that when compared to monitoring stations in the other physiographic regions in the river basin one could expect that UCFRB monitoring stations included in this study would exhibit 160 percent more NO2-NO3 concentrations in surface water systems located in this region (Table 15).

Although nitrogen is required by all organisms to support the basic process of life, inorganic forms may cause adverse impacts to both aquatic and atmospheric processes. Nitrate-Nitrite Nitrogen (NO2-NO3) are inorganic forms of nitrogen and sources include the atmosphere (car emissions), untreated or inadequately treated wastewater from sewage treatment plants, agricultural and stormwater runoff, and poorly functioning septic systems.

Table 15. Model Summary of Nitrate-Nitrite Nitrogen Across the Cape Fear River Basin from October 2000 to October 2001.

Model	**Independent Variables**	**Model r^2**	**Unstandardized b Coefficient**	**Exponent Value**	**Percent Change**
1	Constant	0.15	-.944		
	UCFRB Region		.958	2.60	160%
	p- value <0.05				

The final regression model for NO2-NO3 from October 2000 to October 2001 can be formally expressed as follows:

Log NO2-NO3 (2001) = -0.944 + .958 **UCFRB**

Where,
UCFRB = Upper Cape Fear River Basin

As previously noted, the UCFRB is the most urbanized region within the river basin, however, agricultural and forested land types characterized the largest percentage of the landscape. In the City of Durham, which is partially located in the UCFRB, Carle at al. (2005) observed that increases in total nitrogen in stream systems was positively associated with development density. Wastewater treatment plants (WWTPs) spills and leaks in urbanized areas and septic systems in rural areas have been associated with increases in both fecal and nutrients in surface waters (Cahoon et al., 2006). In addition, increases in nutrients associated with fertilizer applications have been well documented to be positively correlated with agricultural and forested land (Smith et al., 2013; Fink & Mitsch, 2004; Mallin & Cahoon, 2003 and others). For example, silviculture practices also apply fertilizers in an effort to produce a higher yield of timber products. Likewise, this can occur in urban areas where fertilizers are applied to residential lawns and commercially landscaped areas to promote plant growth. Although knowledge of fertilizer applications on agricultural, forested, and residential landscapes are beyond the scope of this analysis, seasonal difference in NO2-NO3 may be driven by human activities on the landscape rather than landscape changes alone. Given the vast array of sources of NO2-NO3, the spatial pattern of the land types that have been associated with increases in NO2-NO3 to surface water systems, and the excessive amount of documented WWTPs leaks and spills, it is not surprising that this region is statistically associated with increases in NO2-NO3 when compared to the other regions in the river basin. The landscape patterns in the UCFRB and the models prediction that it is statistically significant and positively correlated to increases in NO2-NO3 supports a majority of the literature that has observed similar relationships across other watersheds with comparable landscape patterns.

Nitrate-Nitrite Nitrogen (NO2-NO3) October 2006 to October 2007

The LCFRB region was the first and only predictor variable to enter the regression model explaining the spatial variability of NO2-NO3 concentrations from October 2006 to October 2007 (i.e. 2006). The model suggests that the LCFRB region alone explained 8 percent of the variability in NO2-NO3 across the river basin in 2006. The b coefficient associated with the LCFRB region predicts that when compared to the other physiographic regions, one would expect a 76 percent decrease in NO2-NO3 concentrations in surface waters located in the LCFRB region. The F-score was 6.44 and the model is significant at the 5 percent confidence level (Table 16).

Table 16. Model Summary of Nitrate-Nitrite Nitrogen Across the Cape Fear River Basin from October 2006 to October 2007.

Model	**Independent Variables**	**Model r^2**	**Unstandardized b Coefficient**	**Exponent Value**	**Percent Change**
1	Constant	0.08	-0.31		
	LCFRB Region		-0.76	0.46	-76%
	All P values <0.05				

The final regression model for NO2-NO3 from October 2006 to October 2007 can be formally expressed as follows:

Log NO2-NO3 (2006) = -0.31-0.76 **LCFRB**

Where,

LCFRB = Lower Cape Fear River Basin

Land types in this region included the largest percentage of woody wetlands (25%) across the three physiographic regions, 23 percent evergreen forest, and 23 percent cultivated cropland. Changes in the landscape over time were small with increases in cultivated cropland (1.58%), and exurban development (0.12%) and notable decreases in shrub/scrub land (0.64%), evergreen forest (0.58%) and woody wetlands (0.39%). The inclusion of the UCFRB in 2001 and the LCFRB in 2006 may be due to regional differences related to climatic characteristics and ecological differences between the two regions. For example, the LCFRB region contains the largest river estuarine system in North Carolina with an open connection to the sea, which allows for high flushing and flow velocities, which may influence the amount of pollutant concentrations at a given time during the day. When considering how the UCFRB and MCFRB influence water quality in the LCFRB, studies have correlated rainfall in the upper portions of the river basin to lagging flow rates in the LCFRB. In addition, the salinity in the water column in this region has been associated with decreases in nitrate and seasonal differences include elevated surface nitrate during high flow months of December through February with occasional peaks in the summer months (Mallin et al., 1999). As previously mentioned in the 2001 model, fertilizer applications have been linked to increases in nitrogen loading in surface water systems and the ability of vegetative stream buffers to reduce nitrogen loading are varied. Binkley et al. (1999) suggested that the rate of fertilizer applications may affect stream water concentrations of nitrate, however, in their review of several studies, relatively high rates of fertilization typically did not lead to nitrate levels that exceeded water quality guideline. Although this model is statistically significant, it contradicts a growing body of literature that have statistically linked increases in NO2-NO3 concentrations in surface waters located in the LCFRB region. Many of the stations included in this analysis are located along or near the main stem of the Cape Fear River, so tidal influences along with increased salinity in the water column may influence the results found in this model.

Ammonium Nitrogen (NH3-N) October 2000 to October 2001

The first and only predictor variable to enter the regression model for ammonium nitrogen (NH3-N) was percent developed, high intensity (DHI). The model illustrated that DHI explains 17 percent of the spatial variability in NH3-N across the river basin in 2001. The F-score for the model is 14.65 and the model was significant at the 5 percent confidence level. The b coefficient associated with DHI predicted that a one percentage point increase in DHI across the river basin will result in a two percent increase in NH3-N concentrations (Table 17). Percent, developed high intensity is defined as highly developed areas where people reside or work in high numbers. Examples include apartment complexes, row houses, and commercial and industrial development. Impervious surfaces for this land type account for 80 to 100 percent of the total cover. Although this model does not explain a large portion of the variability of NH3-N across the river basin, as the basin continues to become more urbanized, it will become increasingly important to understand how this land type spatially influences concentrations of NH3-N in surface water systems across the CFRB.

Table 17. Model Summary of Ammonium Nitrogen Across the Cape Fear River Basin from October 2000 to October 2001.

Model	Independent Variables	Model r^2	Unstandardized b Coefficient	Exponent Value	Percent Change
1	Constant	0.17	0.08		
	% Developed, High Intensity		0.02	1.02	2%
	p-value <0.05				

The final regression model for NH3-H in 2001 can be formally expressed as follows:

Log NO2-NO3 (2001) = 0.08 + 0.02 **DHI**

Where,

DHI = Percent Developed, High Intensity

Ammonium nitrogen (NH3-N) is typically associated with anthropocentric emissions to the atmosphere, landfill leachate, excreta from humans and domestic animals including livestock and pet waste, synthetic fertilizers, and biomass burning. Intense development is typically associated with a high percentage of impervious surfaces that are linked to high populations of humans, stormwater systems that rapidly convey untreated nonpoint sources of pollution to nearby river and stream systems, increases in domestic pet waste, and high concentrations of WWTPs and related infrastructure (Brabec, 2002; Rothenberger et al., 2009; Arnold & Gibbons

1996 and others). Increases in nutrients to surface water systems may stimulate plant growth resulting in algal blooms that may cause hypoxic (low dissolved oxygen) conditions and increases in water temperatures that may threaten native aquatic species and the overall health of the ecosystem. As previously noted, impervious surfaces that cover greater than 10 percent of the landscape have been associated with stream impairment. In an extensive review of the literature, Brabec et al. (2002) noted that stream degradation related to nutrient concentrations was typically associated with 42 percent or greater impervious surface. In contrast, Mallin et al. (2009) observed difference in ammonia concentrations across rural, suburban, and urban watersheds and concluded that there were no difference in ammonia concentrations across the different watershed types. It is more likely that in a watershed characterized by high percentages of impervious surfaces, sources of NH3-N in surface waters may come from the atmosphere from car and industrial emissions, pet waste from dogs and cats, and fertilizers used in residential and commercially landscape areas (i.e. apartment and business complexes). This model supports a majority of the literature that found associations with intensely developed landscapes and increase in NH3-N in surface water systems.

Ammonium Nitrogen (NH3-N) October 2006 to October 2007

The first and only predictor variable included in the 2006 model for NH3-N was percent low intensity development (DLI). However, this variable only explained 7 percent of the spatial variation of NH3-N across the river basin in 2006. The b coefficient associated with DLI predicted that a one percent increase in DLI will result in a one percent increase in NH3-N concentrations. The F-score is 5.84 and the model was significant at the 5 percent confidence level (Tables 18).

Table 18. Model Summary of Ammonium Nitrogen Across the Cape Fear River Basin from October 2006 to October 2007.

Model	Independent Variables	Model r^2	Unstandardized b Coefficient	Exponent Value	Percent Change
1	Constant	0.07	-2.978		
	% Developed, Low Intensity		0.01	1.01	1%
	p-value <0.05				

The final regression model for NH3-N in 2006 can be formally expressed as follows:

Log NH3-N (2006) = -2.978 + 0.01 **DLI**

Where,

DLI = Percent Developed, Low Intensity

Developed, Low Intensity (DLI) areas are associated with a mixture of constructed materials and vegetation as well as single family housing units. The results of this model contrast the 2001 model for NH3-N, which highlighted that DHI was the most significant independent variable in shaping the geography of NH3-N across the CFRB. Although there was little change in both DHI and DLI from 2001 (i.e. October 2000 to October 2001) to 2006 (i.e. October 2006 to October 2007), there may have been increased activities (e.g. increases in fertilizer applications) in DLI that may have contributed to these areas being more significant in 2006. Landscapes characterized by DLI encompass 20 to 49 percent impervious surfaces. In the CFRB, DLI is typically found encircling medium and high intensity development. Beyond this parameter, one is likely to find exurban development that borders forest or agricultural land types. From 2001 to 2006, development increased by 0.14 percent with low intensity development accounting for 0.05 percent of this increase. Although this is not a large increase, it is important to highlight that the increase in DLI in the CFRB is an indicator of urban sprawl-like development patterns that are associated with increases in impervious surfaces and poor surface water quality. Several studies have linked degradation of stream water quality with increases in impervious surfaces. Specifically, degradation of streams has been observed in watersheds with 10 percent or more impervious surface coverage. As noted in the 2006 model for NH3-N, this parameter is associated with numerous anthropocentric sources as well as domestic and livestock waste. In areas characterized by DLI, residential fertilization, spatially dispersed road networks, pet waste, stormwater systems, and failing WWTP infrastructure are likely to be the main sources of increases in NH3-N concentrations in surface waters systems. Hatt et al. (2004) linked increases in NH3-N with increases in impervious surfaces, especially when they illustrated a dispersed spatial pattern. In contrast, Wilson & Weng (2010) noted that agricultural land and associated activities contribute the largest concentrations of total nitrogen when compared to other land types including development. Although agricultural land is not typically associated with DLI, since DLI is typically found on the fringe of the urban core and often bordering agricultural land, these practices may be contributing pollution, such as NH3-N, to surface water systems that traverse landscapes characterized by DLI. Although this model only explains 7 percent of the variation in NH3-N across the river basin, it supports a majority of the literature that associates this LULC type with increases in NH3-N in surface water systems.

Phosphorus (P) 2001

The final water quality metric to be analyzed was phosphorus. The only predictor variable to enter the regression model for Phosphorus (P) for 2001 (i.e. October 2000 to October 2001) was the percent evergreen forest. Furthermore, no predictor variables were entered in to the 2006 (i.e. October 2006 to October 2007) model, so there are no predictor variables that explain the spatial variability in P for 2006. The 2001 model suggested that percent evergreen forest explained 9 percent of the spatial variability in P across the CFRB in 2001. The F-score for the 2001 regression model was 6.94 and the model was significant at the 0.05 level. The b coefficient associated with percent evergreen forest illustrated that as the percent evergreen forest increased by one percent, the model predicted a 2 percent decrease in phosphorus in surfaces waters within the CFRB (Table 19).

Table 19. Model Summary of Phosphorus Across the Cape Fear River Basin from October 2000 to October 2001.

Model	**Independent Variables**	**Model r^2**	**Unstandardized b Coefficient**	**Exponent Value**	**Percent Change**
1	Constant	0.09	-1.37		
	% Evergreen Forest		-0.02	0.98	-2%
	p-value <0.05				

The final regression model for P in 2001can be formally expressed as follows:

Log P (2001) = -1.37 – 0.02 **EF**

Where,

EF = Percent Evergreen Forest

Evergreen forest are areas dominated by trees generally greater than 5 meters tall that account for more than 20 percent of the total vegetation across the landscape. More than 75 percent of the tree species maintain their leaves all year and the tree canopy is never without vegetative foliage. According to the US EPA (2014) concentrations of phosphorus are typically low when compared to nitrogen, so a small increase in phosphorus can have significant impacts on aquatic ecosystems. Like nitrogen, phosphorus in freshwater systems can lead to algal blooms which often result in hypoxic conditions. This may result in changes in the abundance and diversity of aquatic species and can even lead to fish kills. Sources of phosphorus are similar to nitrogen and may include WWTPs, runoff from fertilized lawns and cropland, failing septic systems, runoff from animal manure storage facilities and spray fields, drained wetlands, soils and rocks, and commercial cleaning products. In contrast to nitrogen, phosphorus is much less mobile and binds readily to soil particles. When phosphorus in soils is built up in large concentrations through excessive manure applications, both surface export and subsurface losses may occur as these soil particles travel to nearby surface waters (Mallin & Cahoon, 2003; Carpenter et al., 1998; Mallin et al., 1999). A majority of the literature observed increases in phosphorus associated with urban and agricultural areas. Although fertilizers are applied to forestland, especially during silviculture activities such as logging, evergreen forest in the CFRB appear to be representative of undisturbed forestland. Since the movement of phosphorus is associated with soil erosion, runoff and subsurface flow appear to be primary factors in the movement of phosphorus to nearby surface waters. Corbett et al. (1997) argued that when compared to an urban watershed, forested watershed have lower runoff volumes, flow rates and sediment loads. If fertilizers are applied in a forested watershed, such as one dominated by evergreen forest, Corbett et al. (1997) suggested that phosphorus concentrations in nearby surfaces waters may still be limited because of reduced surface runoff. This model supports a majority of the literature that found decreases in phosphorus in undisturbed areas, such as evergreen forest, when compared to landscape that have been altered by human activities. It should be noted that from October 2000 to 2001 to October 2006 to October 2007 evergreen forest land types have declined 0.20 percent and often times have been replaced by development or agricultural areas, both of which are associated with increases in P in local surface waters. If this landscape trend continues in the CFRB, it may increase concentrations of P in water systems throughout the river basin. Although this model only explains 7 percent of the variability in P across the river basin, the inverse correlation suggests that conserving or re-establishing evergreen forestland may assist in reducing concentrations of P throughout the river basin.

Regression Analysis Summary

The primary goal of this research analysis was to spatially illustrate and explain relationships between land types and water quality parameters across the Cape Fear River Basin from October 2000 to October 2001 (i.e. 2001) to October 2006 to October 2007 (i.e. 2006). The following research questions were developed to identify the geography of water quality across the river basin.

(Q1) To what extent, and how do, changes in LULC types influence surface water quality at the river basin scale?

When considering how and to what extent changes in LULC types influence surface water quality in the CFRB, the results of the regression models illustrate several statistically significant relationships. It was anticipated that changes in LULC types from forestland to urban land types would dramatically impact surface water systems and that transitions from agricultural land to development would not yield as significant of a change in water quality. In relation to fecal coliform concentrations in 2001 the regression model predicted that a one percent increase in exurban development land will increase fecal concentrations by 5 percent in water quality monitoring stations included in this study across the CFRB. In addition, a one percent increase in mixed forestland increased fecal concentrations by 18 percent. Both of these LULC types are conducive to human disturbances and activities as well as representing transitional landscapes that have been disturbed by human activities. GIS analysis illustrated that a large majority of these land types border developed and agricultural land, further highlighting their transitional nature. In 2006, percent mixed forest, exurban development, and shrub/scrub were included in the regression models. There was a slight decrease in the relationship between percent mixed forest and fecal concentrations with the 2006 model suggesting that a one percent increase in mixed forest land would yield a 13 percent in fecal concentrations at monitoring stations across the river basin. In relation to exurban development, the 2006 model predicted that this land type would have less influence on the concentrations of fecal when compared to the 2001 model for stations included in this study. The regression model also predicted that a one percent increase in shrub/scrub land would increase fecal concentrations in surface water systems by 7 percent holding all other predictor variables fixed.

When considering associations between land types and dissolved oxygen (DO), the 2001 model predicted that a one percent increase in emergent herbaceous wetlands would decrease fecal concentrations by 7 percent holding all other predictor variables constant. This relationship held true in the 2006 model for DO. A majority of the literature supports this finding because wetlands are typically low in DO as a result of the low flows or stagnant water conditions that naturally occur in these areas.

High concentrations of nutrients (NO2-NO3, NH3-N, and P) have been well documented to cause numerous water quality issues including algal blooms that result in hypoxic (low DO) conditions. Ecologically, this may result in a reduction in the number and diversity of aquatic species. There were no statistically significant relationships between individual land types and NO2-NO3, however, high intensity development (2001) and low intensity development (2006) were statistically significant in relation to NH3-N concentrations and evergreen forest were inversely related to phosphorus concentrations in 2001. The regression model for NH3-N in 2001 predicted that a one percent increase in high intensity development increased NH3-N levels by two percent, while the 2006 model predicted that a one percent increase in low intensity development increased NH3-N by one percent at stations included in this study. Ammonium nitrogen comes in many forms and has been linked to both developed and agricultural land. Common sources in both high intensity and low intensity development include fertilizer applications on residential and commercial properties, human and pet waste. Sources of phosphorus mimic many of the sources of NH3-N causing similar impairments to surface water systems and related aquatic ecosystems. The 2001 model for phosphorus predicted that as the percent evergreen forest increased by one percent, concentrations of P decreased by two percent. As previously mentioned, nutrients can be found naturally in forested landscapes, however, human activities, such as silviculture practices, may require additional applications of fertilizers and pesticides that can enrich surface waters leading to degraded water quality and impaired ecosystems.

The results of the regression models for fecal, DO, and nutrients support a majority of the literature that seeks to understand these relationships. Although there was little change in the landscape across the river basin from 2001 to 2006, the results of this regression analysis illustrate statistical relationships between specific land types and the geography of water quality across the CFRB. It appears that both development (i.e. low and high intensity development) and transitional land types (i.e. mixed forest, shrub/scrub land, and exurban development) are influential in adversely impacting surface water quality across the basin. As LULC types and patterns continue to transition across the CFRB, it will be increasingly important to not only understand the impacts of these transitions on water quality, but to document the various activities on these landscapes in an effort to gain a better, more holistic, understanding of these relationships across the entire river basin.

(Q2) To what extent does development influence surface water quality at the river basin and across the different physiographic regions?

It was anticipated that less-urbanized areas will exhibit poorer water quality when compared to highly urbanized areas. The regression models for fecal coliform for 2001 (i.e. October 2000 to October 2001) and 2006 (i.e. October 2006 to October 2007) support this assertion because the exclusion of highly developed land types from these models signifies that less developed areas are more influential in shaping the geography of fecal concentrations across the basin. When considering relationships between development and nutrient concentrations, the 2001 regression model for NH3-N predicted that high intensity development would increase NH3-N concentrations in stations included in this study by 2 percent, while in 2006 a one percent increase in low intensity development increased NH3-N concentrations by one percent. Although each of these models discussed are statistically significant, the 2006 model for fecal coliform shows the most dynamic relationship between less urbanized land and increase in fecal concentrations across the CFRB. This model supports the hypothesis that less urbanized areas will exhibit poorer water quality when compared to high intensity development, but only when considering fecal concentrations at stations observed in this study.

When observing development and water quality across the three physiographic regions, the UCFRB region represented the most urbanized physiographic region in the CFRB as well as the region that was most frequently included in the regression models. This region experienced the highest number of stations that exceeded the state guideline for fecal in both years. The regression models statistically illustrated that when compared to the other physiographic regions, one would expect 110 percent higher fecal concentrations in 2001 and 96 percent more fecal concentrations in 2006. In relation to NO2-NO3 in 2006, the regression analysis predicted that this region experienced 160 percent higer NO2-NO3 concentrations when compared to other regions. These relationship support a majority of the literature that has linked similar landscape patterns with water parameter concentrations. When considering regional differences in DO across the river basin, the regression analysis predicted that compared to the other regions, the MCFRB experienced a 16 percent increase in DO concentrations in 2001. This may be due to the nature of land patterns in this regions, which are primarily wetlands and forestland. Lastly, the LCFRB region exhibited inverse relationships with both DO and NO2-NO3 concentrations in 2006. In relation to DO, the regression analysis suggested that when compared to the other physiographic regions, stations in this LCFRB that were included in this study showed 9 percent lower DO concentrations. This inverse relationship may be due to both natural landscape features, including wetlands and blackwater streams, as well as land activities (e.g. CAFOs) associated with agricultural land. The regression analysis for NO2-NO3 in 2006 predicted that when compared to the other regions, stations in the LCFRB that were included in this study would exhibit 76 percent less NO2-NO3. This result is in contrast to a majority of the studies conducted in this region. This may be due to the exclusion of several water quality monitoring stations located in watersheds characterized by a large concentration of CAFOs (see Caveats).

(Q3) To what extent and how do agricultural land types influence water quality at the river basin and across the different physiographic regions?

It was anticipated that pollution inputs entering stream and river systems in physiographic regions dominated by agricultural land would exhibit variation in the amount of pollution concentrations because of differences in seasonal and annual activities on these landscapes (e.g. fertilizer applications, crop rotations, etc.). GIS analysis illustrated that although each of the physiographic regions has unique landscape patterns, each of the regions are primarily represented by forested land. Although agricultural land types were not included in any of the regression models, the number of permitted livestock headcount, which represented activities associated with agricultural land, was statistically associated with 16 percent lower DO concentrations. This predictor variable may include grazing livestock in addition to livestock associated with confined or concentrated animal facility operations (CAFOs). Spatially, grazing livestock are typically found in the UCFRB region and upper portion of the MCFRB region, while CAFOS are geographically concentration in the lower portions of both the MCFRB and LCFRB regions. Since the livestock permit headcount only represented the *maximum* number of livestock a permit holder can obtain at a given time, there is no true understanding of how many actual livestock are on the landscape or in confined facilities when water quality samples are collected. To better understand the relationships between these two variables, Mallin and Cahoon (2003) and others have been able to estimate the amount of nutrients in animal manure produced by CAFO activities. Applying a similar method to grazing livestock may facilitate a better understanding of the relationship between the number of livestock and nutrient concentrations in surface waters. This is an important component in further understanding how nutrient enrichment in surface waters may create hypoxic conditions throughout the river basin

CHAPTER V

CONCLUSION

As the population in the Cape Fear River Basin (CFRB) continues to grow it will become increasingly important to address the geography of surface water quality throughout the basin. Although past research has identified some relationships that exist between land-use/land-cover (LULC) types and surface water quality at the local watershed level and across a single physiographic region, a comprehensive study that specifically addresses the spatial distribution of these relationships across an entire river basin has been less common. The overall goal of this research was to identify and spatially illustrate the geography of water quality and its relationship to varying land types across the entire Cape Fear River Basin (CFRB) from October 2000 to 2001 (i.e. 2001) to October 2006 to October 2007 (i.e. 2006). Key questions included how, and to what extent, do specific LULC types impact surface water quality both across the entire basin and within each of the separate physiographic regions.

Descriptive statistics were analyzed to identify LULC types and water quality trends across the river basin as well as to identify key watersheds within each physiographic region that experienced significant changes in water quality from 2001 to 2006. Although there were only small changes in LULC types over time, specific land types were still linked to water quality impairment at the river basin scale. In addition, there were differences in these relationships between the three physiographic regions. When observing LULC changes alone, each region had increases in agricultural land and development and decreases in forestland. The MCFRB experienced the largest increase in development, which may be due to the increasing population associated with the Fort Bragg Military Base. The LCFRB experienced the largest increase in agricultural land among the regions and the most significant decrease in wetlands. Although each of the physiographic regions lost forestland, the MCFRB experienced the largest decrease in forestland, which may be associated with increases in development. The decrease in forestland across the river basin and the increase in both agricultural and developed land suggested that, although there are small changes in the landscape, there is a landscape transition taking place across the river basin as well as within each of the physiographic regions.

Another significant finding was the trend in fecal concentrations from 2001 and 2006 at the river basin scale. Stations included in this study that exceeded the state guideline for fecal in 2001 were largely concentrated in the UCFRB, while in 2006, they were more spatially distributed throughout the river basin. In addition, watersheds that drain to stations exceeding the state guideline for fecal were characterized by both mixed and forest land types. These finding suggested that various land types and patterns may contribute to increases in fecal concentrations in surface waters at different geographical scales. Further research found that significant sewer spills occurred throughout the river basin during this time period signifying that land types alone may not be the primary factor contributing high concentrations of fecal to surface waters in the CFRB. Other significant findings included both spatial and seasonal differences in dissolved oxygen (DO) across the river basin.

In addition to the descriptive analysis, regression models were developed to statistically demonstrate the extent to which specific land types impacted surfaces waters from 2001 to 2006. The results of the regression analysis assisted in identifying how the relationships between LULC types and water quality parameters varied across the entire CFRB as well as by physiographic region. In relation to fecal coliform concentrations, percent mixed forest was the most significant LULC type that was predicted to increase fecal concentrations in both 2001 and 2006. As previously noted, this land type has been identified with human disturbances such as a transition from forest land to both agricultural and urban areas. Mixed forest in the CFRB was typically found along the fringes of these areas indicating that it may become more developed over time. In addition, shrub/scrub land was also associated with an increase in fecal concentrations in 2006. This land type has been identified with human disturbances such as land clearing and transitional borders between forestland and agricultural and urban landscapes. As a result, transitional landscapes that are inclusive of exurban development and mixed forest appear to play a critical role in shaping the geography of water quality across the CFRB. Furthermore, it is important to note that transitional landscapes may be present in other watersheds. Figure 36 illustrates a conceptual diagram of how the relationships observed in the CFRB may impact surface water quality in watersheds with similar landscape features and patterns. The hypothetical illustration highlights how one of the most substantive factors in shaping the geography of water quality in the Cape Fear Basin – fecal coliform spikes – is more likely to occur in transitional areas linked to exurban development and mixed forest, especially when located near to WWTP's and CAFO's. When considering each of the physiographic regions and their relationship to fecal concentrations, the UCFRB was the only region identified in the regression models for both 2001 and 2006 for fecal concentrations. Compared to the other regions within the river basin, monitoring stations in the UCFRB exhibited 110% higher fecal concentrations in 2001 and 96% higer in 2006. This is a significant finding because the UCFRB serves as the headwaters of the CFRB and impacts on water quality in this region can compound water quality issues in surface water systems in regions located downstream.

Another noteworthy result of the regression analysis highlighted the relationships that exists between DO, physiographic regions, and LULC types. In 2001, increases in DO were associated with the MCFRB region and decreases were linked to wetlands. The MCFRB is primarily characterized by evergreen forestland that are highly dispersed throughout the region.

The results of this analysis suggested that increases in DO in this region in 2001 may be associated with this dispersed land type in addition to topographical changes in the stream profiles as this region transitions from the piedmont to the sandhills of coastal North Carolina. Furthermore, although there are concentrations of development in this region, there is less development throughout the MCFRB when compared to the other physiographic regions. The 2006 regression model for DO suggested that decreases in DO were primarily associated with the LCFRB and the number of permitted livestock headcount. The LCFRB is characterized by concentrated development patterns primarily surrounded by dispersed forested land and high concentrations of agricultural practices, including CAFO activities. In addition, the LCFRB contains several blackwater streams and wetlands that are naturally low in DO. It should also be noted that in both 2001 and 2006, decreases in DO were associated with wetlands, which supports a majority of the literature.

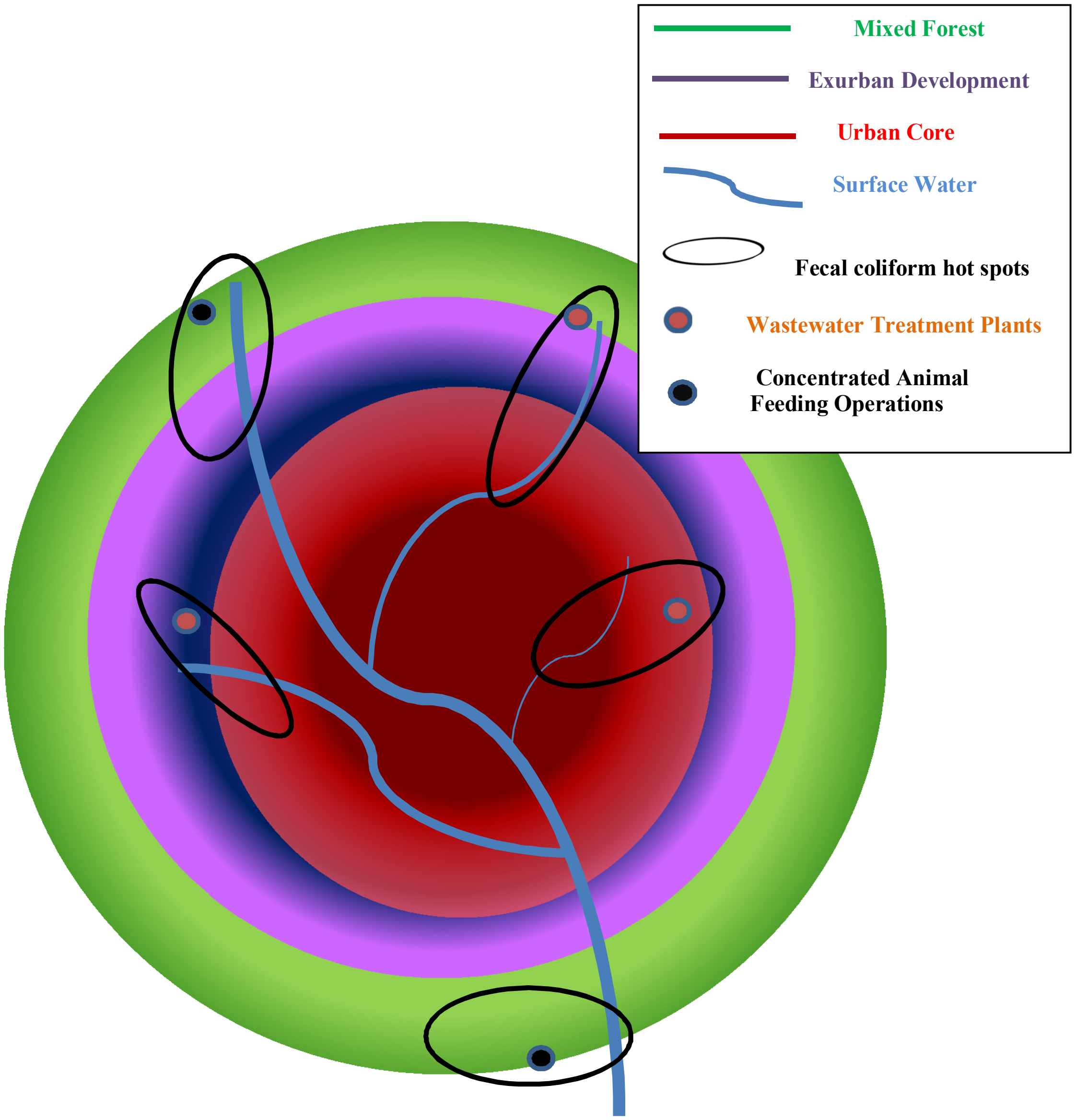

Figure 36. Conceptual Diagram of Relationships between LULC Types, Patterns, and Features and Potential Impacts to Surface Water Quality Across a Watershed.

The findings of both the descriptive statistics and regression analysis assisted in identifying four primary conclusions. First, observing the geography of water quality at the river basin scale facilitates the identification of transitional landscapes across the basin that may be missed when analyzing specific physiographic regions within the basin. Second, activities and events that cause increases in water quality parameter concentrations may have short and long term impacts as well as local, regional, and basin wide impacts. For example, the large quantities of sewer spills in the UCFRB may have adverse impacts to surface waters within close proximity of the spills, but since these surface water systems move downstream, traversing multiple physiographic regions and watersheds, it may be impacting surface water systems across the entire river basin. Third, observing relationships between water quality and specific land activities rather than land types alone may allow for a more comprehensive understanding of these relationships across the river basin. This study observed that even within a single physiographic region, the same land types may have varying impacts on surface water quality possibly indicating that various activities on the landscape may be adversely impacting surface water quality. Lastly, there are regional differences between land types and water quality parameters across the river basin. Across all of the water quality parameters, the UCFRB appears to have the most significant impact on surface water quality. This has not only been linked through statistical analysis, but also through extensive analysis of documented wastewater treatment facility and infrastructure spills. This is a significant finding because the UCFRB is not only the most urbanized and populated region in the basin, but it also serves at the headwaters of the river basin, so activities in the region may be adversely impacting surface water quality downstream.

The results of this research have assisted in identifying several avenues for future research and highlighted the need for more comprehensive data sources and land-use policies. Although the Cape Fear River Basin Coalition has worked with the NC DENR to developing a basin wide monitoring program, there are temporal gaps in data information and all of the stations lack flow data, which may be linked to inconsistent funding of the program. Flow data is essential in understanding the extent to which climatic conditions, human activities, and specific

LULC types impact water quality throughout the basin. Once a more comprehensive data resource is established, research could be conducted that spatially illustrates how climatic conditions and the proximity of specific land types impact water quality as well as the effectiveness of vegetated buffer zones bordering surface water systems. In relation to human activities on the landscape, more data is needed to address the extent to which specific activities (e.g. spraying fecal on fields, development, and fertilizer applications) are impacting surface water resources throughout the river basin. This may assist in understanding how different activities associated with a specific landscapes may be impacting water quality, which could help to develop more comprehensive policies across the river basin aimed at protecting water resources.

Clean water is essential for all living organisms. As the population of the CFRB continues to grow, more demand will be put on the landscape and this increase in activities may lead to new sources of water impairment. If water resources are not protected there could be both health and economic risks that hinder the river basin's ability to support a growing population. In addition, costs associated with cleaning up polluted waters may well exceed costs associated with protecting this vital resource. Funding has often been a limitation in resolving these issues. Citizens and decision makers alike should consider how mitigating impacts through a proactive approach may reduce short and long term costs. In an effort to mitigate these impacts, researchers, citizens, and decision makers need to collaborate in an effort to develop comprehensive strategies aimed at protecting these vital resources at the local, regional, and basin wide scales. If decision makers at the local and regional scales are aware of basin wide trends in both landscape changes and water quality, they could then develop more comprehensive policies that benefit the river basin as a whole. Taking into consideration how economic, social, and cultural activities influence water quality will lead to a more well-rounded approach to protecting water resources that can be sustained for future generations to come.

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